# BIOLOGICALLY BASED UNDULATORY LAMPREY AUV PROJECT

MSEL Report #95-01
Prepared Under Grant #N00014-94-1-1035



Prepared by: Northeastern University
Marine Systems Engineering Laboratory
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PHASE 1

## 1.0. INTRODUCTION

This document serves as the final report for Phase I of this project. The report covers the period from June through December 1994. It includes descriptions of fish biomechanics, kinematic relationships, and neural control concepts. These relationships served as a basis for developing and conducting laboratory experiments aimed at demonstrating the feasibility of creating systems capable of generating smooth undulatory motion similar to that of fish, particularly Lamprey. This report also presents a description of the systems developed, experiments conducted, and the results of these experiments. This work was sponsored by ARPA and ONR under grant number N00014-94-1-1035.

## 1.1 BACKGROUND

There is much to be learned from the way that ocean creatures propel themselves. They have evolved systems which allow them to exhibit complex motion and behavior. During the last two decades substantial progress has been accomplished internationally in understanding some of the basic principles.

Fish use hydrodynamically streamlined bodies to reduce drag and undulatory movement to produce thrust. These movements are generated by alternating muscle contractions on both sides of the body. The rostral (front) segments contract earlier than the caudal (rear) segments. The amplitude of these movements varies along the body and differs between species, but is directly related to the fish form and its rigid and elastic properties. The swimming movements (thrust generating mechanisms) are controlled by a segmental network (spinal pattern generators) whose activity is controlled in a rather simple way (one or two parameters) to produce stereotyped swimming movement. Fish bodies are made up of 24 to over 100 segments of skeletal, muscular, and nervous elements. The problem of mechanical and nerve control can be addressed by reducing the number of degrees of freedom. The mechanical problem is solved by the proper distribution of inertial, elastic, and hydromechanical properties. The nerve problem is solved by the proper coordination of inter-segmental interactions.

## 1.2 PROGRAM GOALS PHASE I

The goal of this phase of the program is to make use of known neural control systems and biomechanic relationships in fish to empirically investigate and demonstrate means of generating smooth undulatory motion similar to that of fish, particularly Lamprey. This phase utilized Shape Memory Alloy (SMA) technology to simulate fish muscles and to provide the needed contrac-

tion mechanism.

## 2. FISH BIOMECHANIC AND KINEMATIC RELATIONSHIPS

As mentioned earlier, significant progress has been achieved during the last two decades in understanding mechanisms of fish swimming. Kinematics, fish muscle activity, synergies of fish myotomes, neural pattern generators and command centers were extensively investigated [references 1 to 26]

Bodyform: The fish body is usually an elongated streamlined form. Length to depth ratios of 4:1 - 6:1 are typical for good swimmers, and are about 10:1 for eel like fish such as Lampreys. The whole fish can be divided into three basic parts: a non-flexible head, an actively flexible middle, and a passively flexible tail.

Axial skeletal systems in fish. Stiffness and flexibility of a fish body depends on the axial skeleton which in some fish consists of the bony vertebra column whereas in others it consists of notochord or cartilage. Stiffness is actively contolled by the muscle fiber contractions. We believe that the fish body as a whole is a self-tuning system so that its stiffness is adjusted to the particular frequency of undulation in the range from approximately 0.5 to perhaps 20 hertz for the majority of fishes.

Passive control of fish undulations is determined by the bodyform and particularly by the distribution of its mass along the bodylength. In fish like mackerel, the center of mass is displaced towards the cranial part to about 1/3 of its body-length, whereas in the eel it is closer to the middle of the bodylength. Figures 1a and 1b are plots of representative data which we measured and which show the relative mass distribution versus body length for these two fish.

Individual segments. Fish musculature and spinal chord are divided into a number of compartments which exactly correspond to the number of vertebrae. Each muscular segment which produces movement consists of left and right myotomes innervated by the ventral roots of the spinal cord which sends commands to the muscle fibers and dorsal roots and which returns information about the produced movement. During swimming activity, segmental pattern generators alternately activate left and right myotomes with half cycle delay between them.

Backbone & Muscles: The mechanical backbone of animals which utilize undulation to generate motion has evolved from the hydrostatic skeleton of invertebrates whose structure permits both undulations and peristaltics to the almost hydrostatic notochord of amphioxus. The latter can change its stiffness by the activation of muscle fibers (paramyosine) lying inside the notochord. The notochord lies along the central axis of the body, contains no bone, and takes up approximately 7% - 10% of the cross sectional area. In Lamprey there is also a cartilageous vertebra column around the notochord.

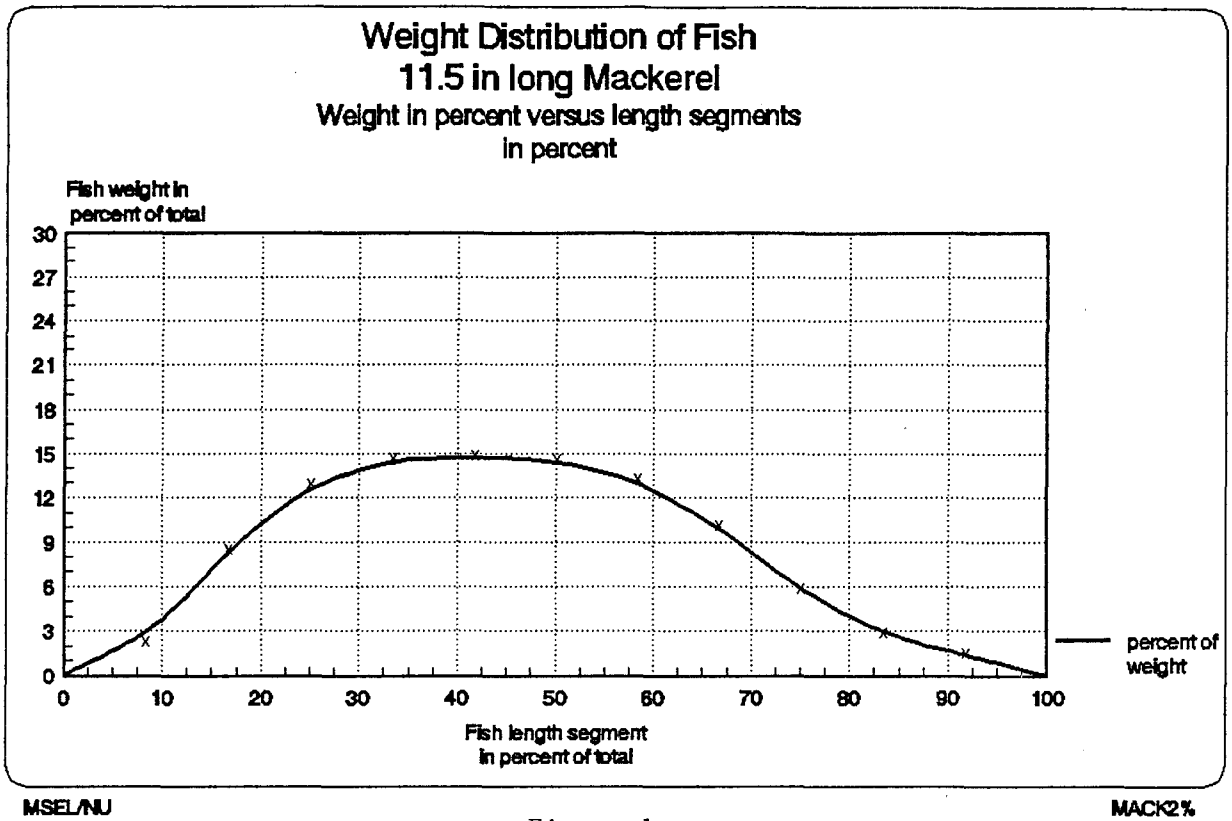


Figure 1a

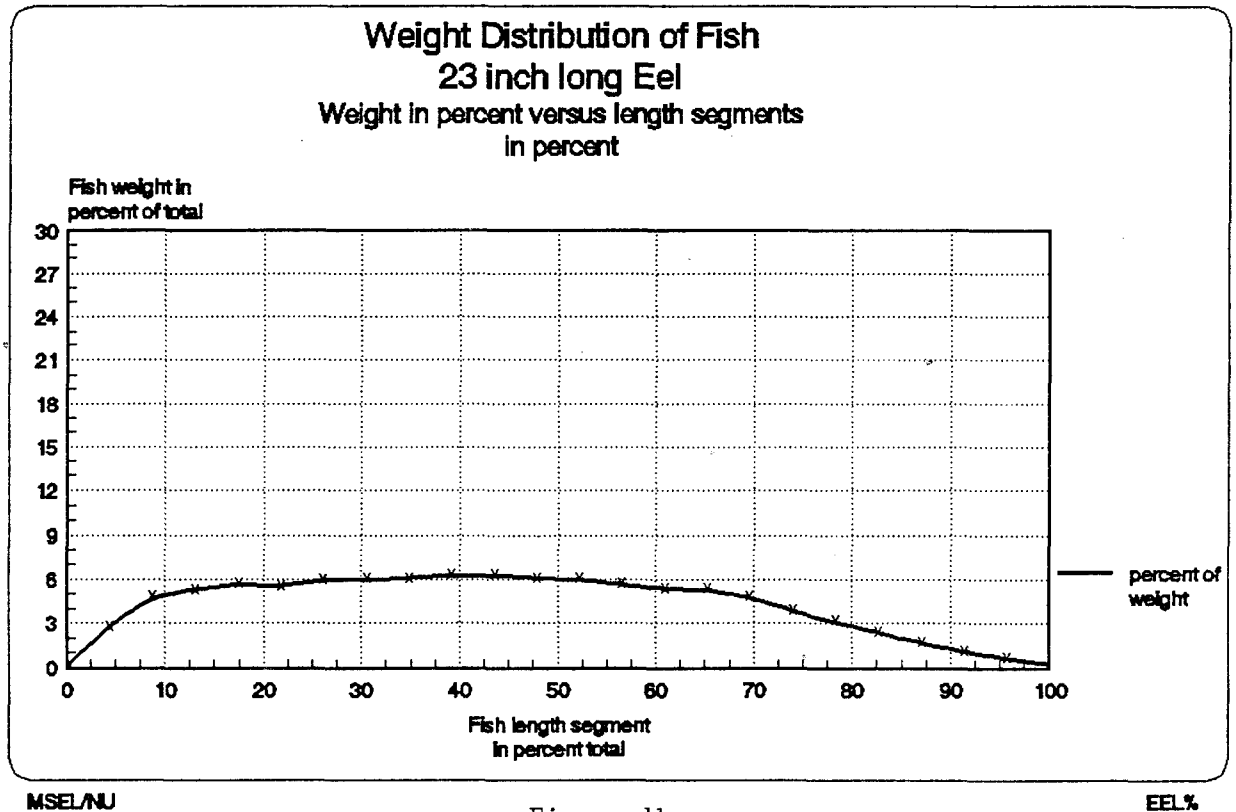


Figure 1b

The fluid of a hydrostatic skeleton has high internal pressure which can be increased by contracting muscles. The pressure in the notochord of vertebrates is created by cell proliferation during the maturation process. Stiffness is controlled by muscle fiber contractions. Whole body musculature consists of myotomes whose number is equal to the number of vertebra. The final evolutionary stage of increasing stiffness included development of solid bones in teleosts.

In fish as in all animals, movements are produced by the contraction of muscle fibers. Muscle fibers are shortened (contracted) by the commands from motoneurons. One motoneuron usually send axons to a number of muscle fibers, the group of muscle fibers, innervated from one motoneuron, is called 'motor unit'. Each muscle fiber contains a number of miofibrillas (about 300 for a 100 micron diameter). Each miofibrilla consists of a series of sarcomeres. Fish sarcomeres are similar to that of other animals. They are about 2 microns in length and contract in normal conditions from 2 to 5% of their length. Each muscle fiber of 5 mm length (which is typical for adult lamprey or any other fish of average size) therefore contains approximately 100,000 to 1,000,000 sarcomeres and all of them have to be activated synchronously to produce maximal force.

The number of sarcomeres in one cell is so large that, to some extent, it is comparable to the number of crystals in shape memory alloy wires. In these wires a reversible crystalline phase transformation occurs by the application and removal of heat, thereby creating a contraction force similar to that of muscle.

Kinematics. Amplitudes of undulations increase from the snout to the tail in all fish. Low speed movement is controlled by the amplitude of the tail whereas high speed (exceeding 2 bodylength per second) is directly proportional to the frequency of undulations (Figure 2a). The tail motion amplitude is nearly constant for the latter case and is approximately equal to 20% of the bodylength for all studied fishes (Figure 2b).

The flexures of the body usually move backwards along the body and their speed is directly proportional to the speed of swimming (Figure 2c). There is usually one wavelength along the fish body for carangiform type of swimming and 1.25 wavelength for the elongated animals like lamprey or eel.

Coordinations and control. Fish can be considered as an undulating rod in a viscous media. The resonant frequency of the system depends on the interaction of the inertial, elastic, and resistance components. The elastic component can be controlled by muscle force which changes stiffness of the body. The system is possibly self-tuned for a range of undulating frequencies from about 0.5 to 20 hertz for a majority of fish.

The wave of muscular activity propagates along the body due to the time delay in activation of the posterior myotomes in com-

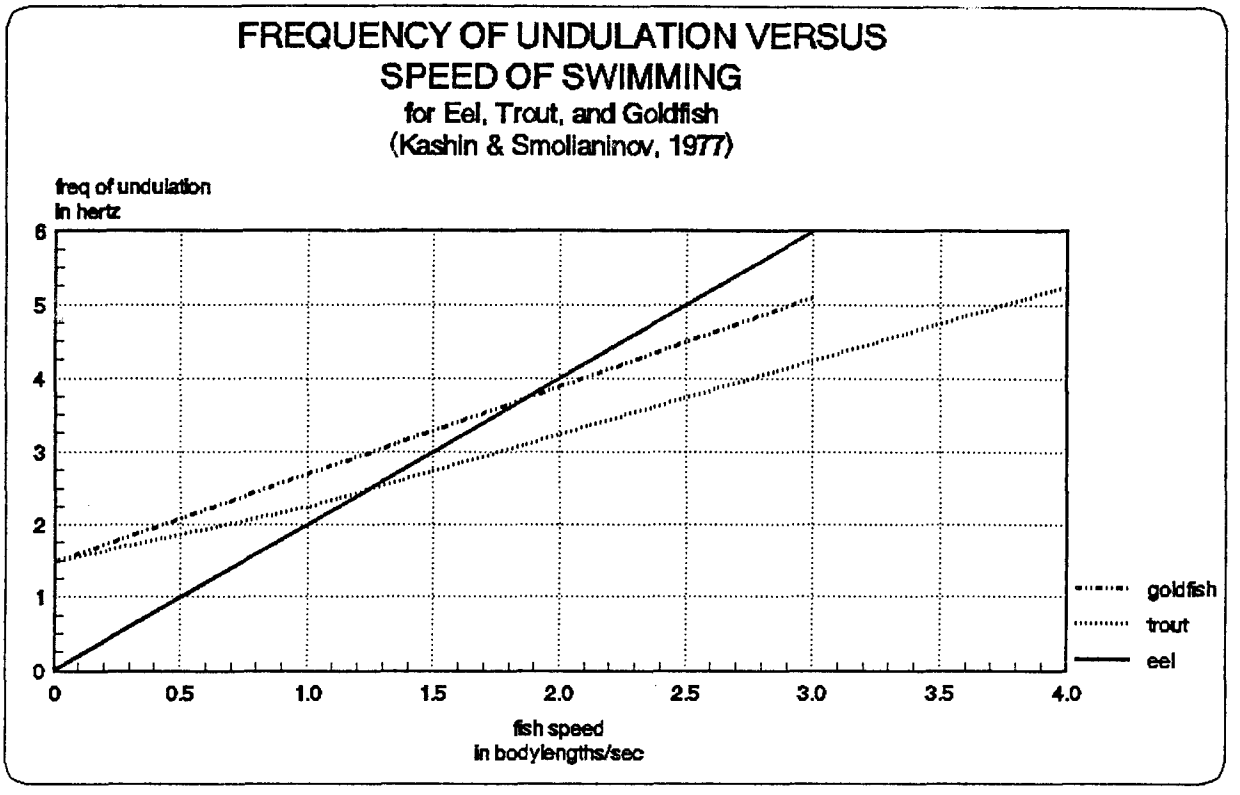


Figure 2a

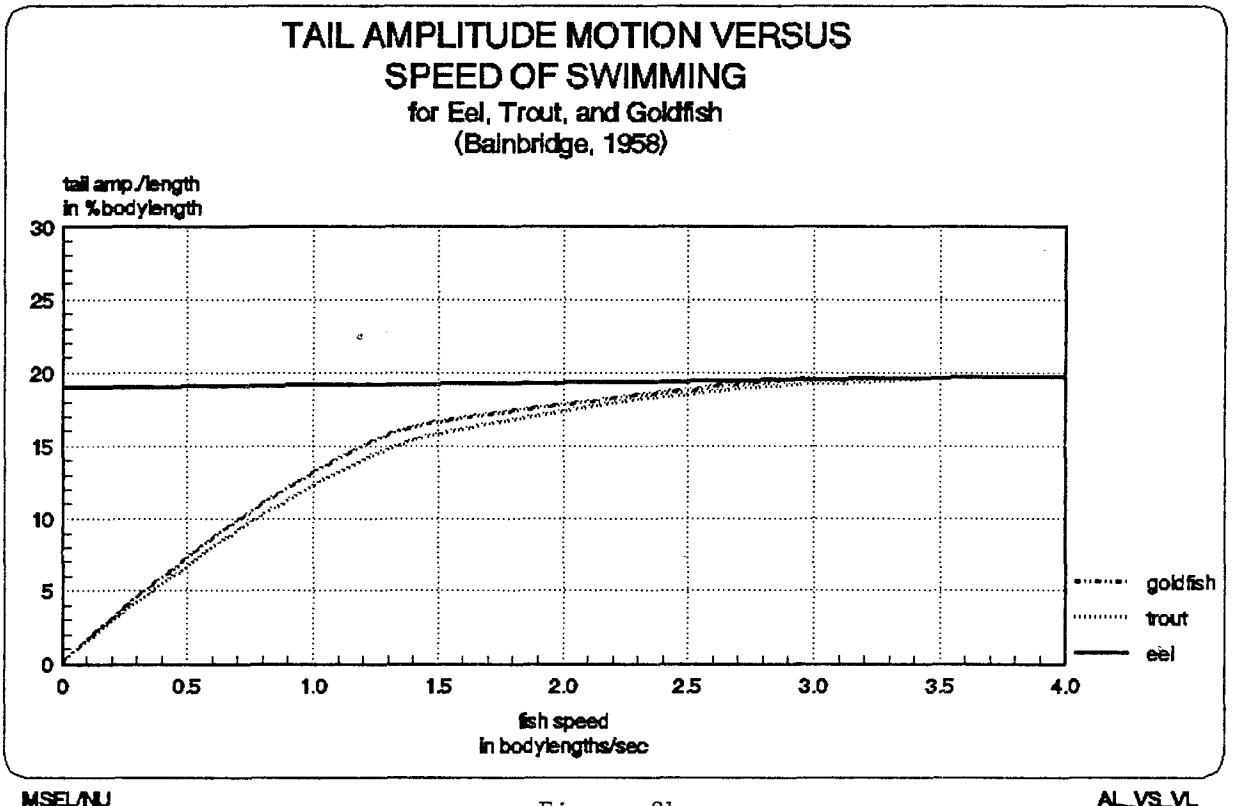


Figure 2b

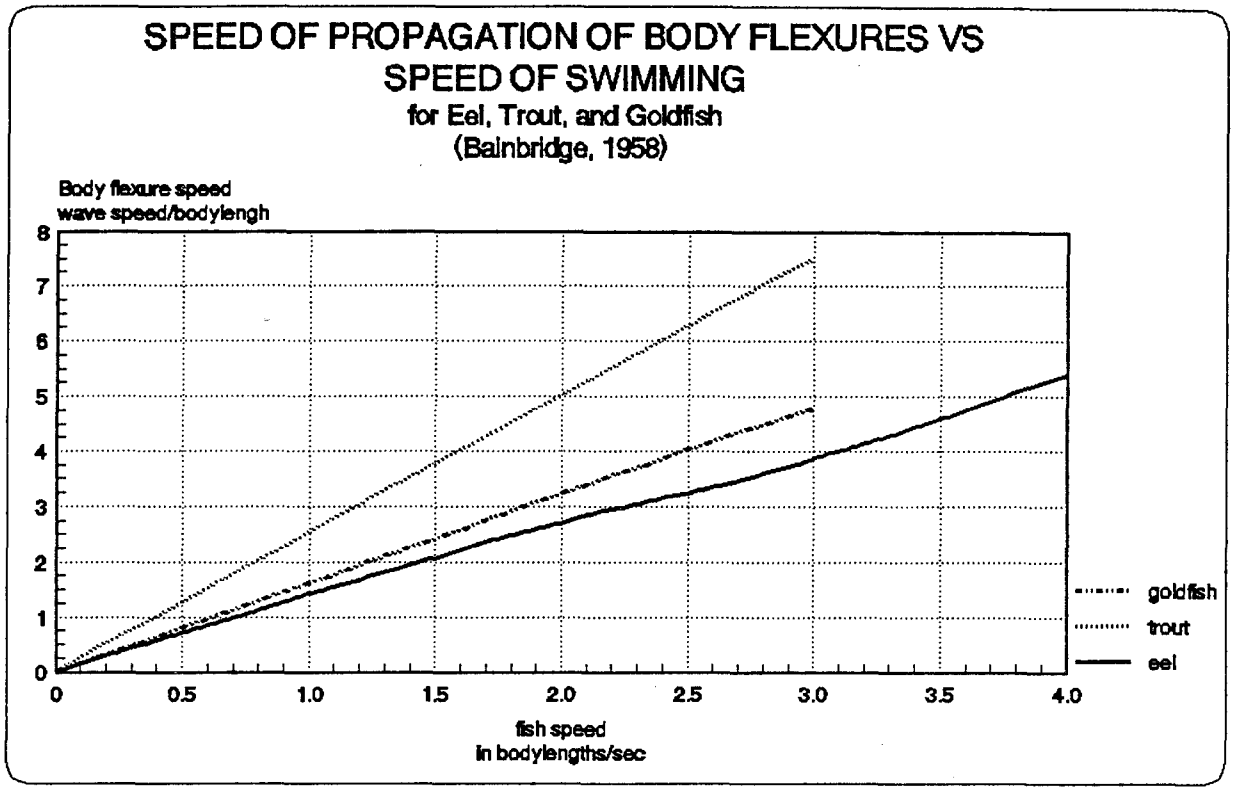
SPEED OF PROPAGATION OF BODY FLEXURES VS
SPEED OF SWIMMING
for Eel, Trout, and Goldfish
(Bainbridge, 1958)
Body flexure speed
wave speed/bodylengh
8
7
6
5
4
3
2
1
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
fish speed
in bodylengths/sec
goldfish
trout
eel
MSEL/NU
WL_VS_VL

Figure 2c

parison with the anterior ones with alternating left and right sides. Although the time delay decreases when the speed of swimming and frequency of undulations increase, its phase lag remains constant so that the time delay is proportional to the cycle duration.

The structure of locomotor cycle in fish in terms of the myotome activations based on electromyographical recordings is shown in Figure 3. Four types of organization or coordination have thus far been described for different species. We will refer to the types of coordination according to the species name for which they were first described.

1. Eel-like or lamprey-like organization of locomotor cycle. Delays between activations of the consecutive myotomes are approximately equal to the delays between ends of their activations (ie Db = De). The activation delay is approximately equal to the cycle duration T divided by the number of segments on a given side. Approximately one fourth of all ipsilateral myotomes are active at any given moment of time.

2. Carp locomotor cycle. Delays between activations and deactivations of consecutive myotomes are shorter than the those in Case 1 above. As a result there is a larger percentage activation than in the first case at any moment of time while swimming.

3. Trout locomotor cycle. This is similar to the first case in terms of delay between activations, however, the myotome burst durations decrease from the snout to tail (Tact1 >Tact2> Tactn).

4. Shark locomotor cycle. The phase delay between activations of myotomes is equal to the burst duration of the first segment (tact) divided by the number of segments on a given side. The burst duration decreases along the body much like the trout-type. The delay between ends of activations however, equal zero (De = 0), hence all activation on a given side ends at the same time. There is only activation on one side at a time for this case.

## 3. SUMMARY OF IMPORTANT BIOLOGICAL RELATIONSHIPS

The following statements are meant to summarize some of the important relationships which have application in developing an undulatory system.

1. The time delay between activation of segments is always a fixed percentage of cycle time.

2. The speed of swimming is proportional to frequency of oscillation and speed of flexure wave propagation.

3. An increase in stiffness is required to increase frequency.

4. The left and right sides of individual segments are alternately activated.



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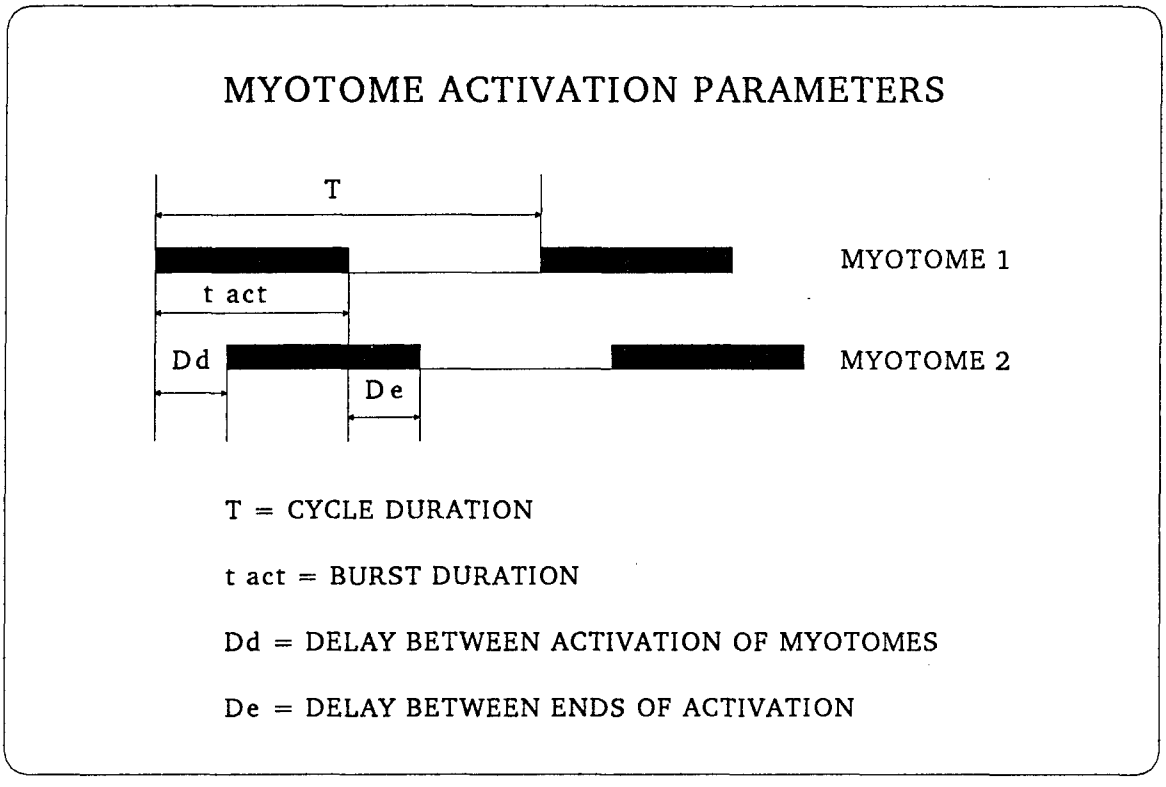

MYOTOME ACTIVATION PARAMETERS
T
MYOTOME 1
t act
Dd
MYOTOME 2
De
T = CYCLE DURATION
t act = BURST DURATION
Dd = DELAY BETWEEN ACTIVATION OF MYOTOMES
De = DELAY BETWEEN ENDS OF ACTIVATION

Figure 3

5. The duration of excitation does not exceed 1/2 of cycle time.

6. Different muscle systems are used for slow and fast swimming.

7. Thrust is in the form of pulses at twice the frequency.

8. Distribution of amplitudes of undulation are directly correlated to basic structure. ie mass, cross section area, and areas of lateral projection.

## 4. UNDULATORY SYSTEM EXPERIMENTS, RESULTS AND ANALYSIS

### 4.1 Shape Memory Alloy (SMA) muscle mechanism

Shape Memory Alloy (SMA) technology and the "shape Memory Effect" is well described in the literature [references 27-42]. References can be found which date back several decades. The most extensively investigated material is the Nickel-Titanium alloy which is usually fabricated as 50% Nickel. Basically, the crystalline structure within the material can be cycled between two geometric states, namely martensite and austensite, by application and removal of heat. When this transition occurs a measurable shape change occurs in the material. In the martensite (cool) state the crystals are in an orthorhombic or elongated form and the material is is relatively limber. When the material is heated above the austensite temperature threshold, the crystals switch to a cubic form which is much tighter and causes the material to contract very rapidly. This transition can be made to occur by the application of electrical pulses. This material then behaves much like an organic muscle fiber. Detailed comparisons of muscle with various types of artificial actuators including SMA mechanisms has been studied by Hunter and Lafontaine [16]. They incidentally have been of great assistance to us in developing a practical understanding of this technology. The power to mass ratio of a nickel-titanium (Nitinol) fiber is about 1000 times greater than muscle. This is without consideration of mass or volume of cooling system should this be required. A plot of the nominal (recommended recovery) force of various diameter wires (Flexinol) is plotted in Figure 4. This is about one third of the maximum recovery force and this value is used to preserve the factory training. The bias force is also plotted in the same figure. This is the force that should be applied to extend the wire as it cools. This value is typically about 5% to 10% of the maximum force.

The contraction time of an SMA wire depends on how fast one can heat the wire, hence is directly dependent on the risetime and amplitude of the current pulse. The relaxation time, however, is dependent on the time it takes to cool the wire (thermal diffusion).

### 4.2 Single Segment Configuration

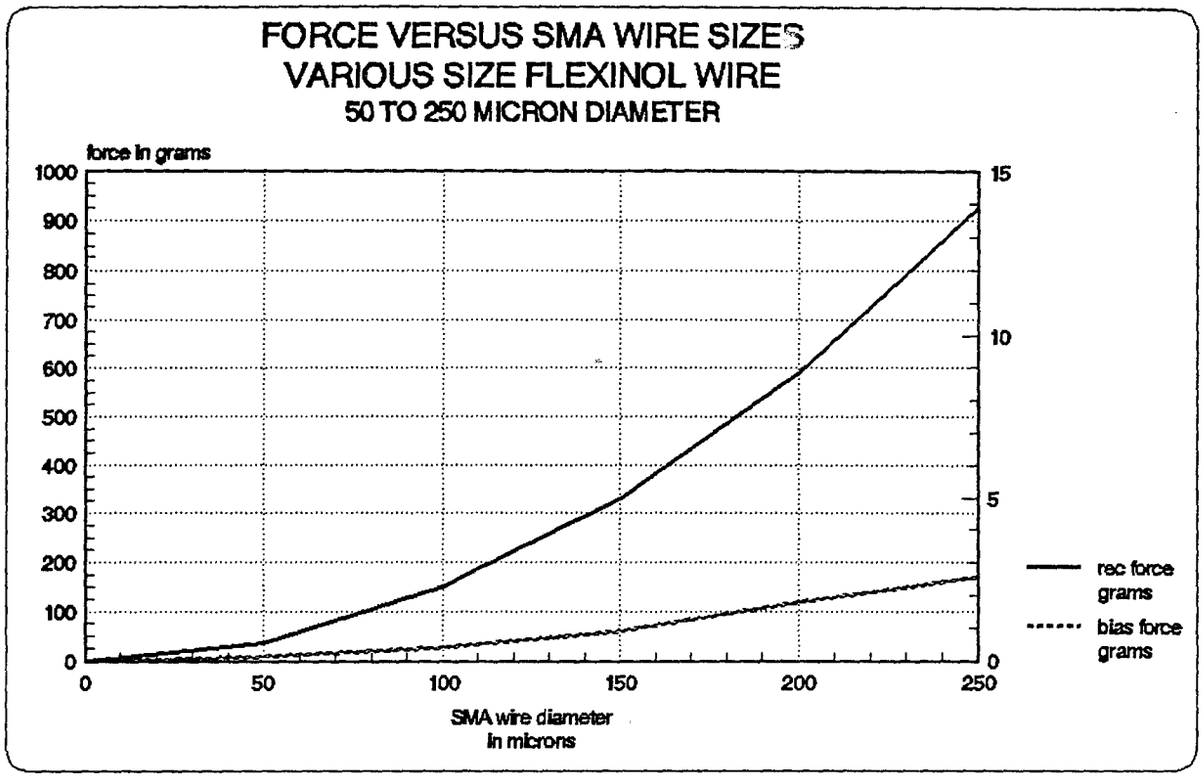

FORCE VERSUS SMA WIRE SIZES
VARIOUS SIZE FLEXINOL WIRE
50 TO 250 MICRON DIAMETER
force in grams
1000
900
800
700
600
500
400
300
200
100
0
15
10
5
0
0
50
100
150
200
250
SMA wire diameter
in microns
rec force
grams
bias force
grams
MSEL/NU
SMAFORCE

Figure 4

The basic system envisioned to demonstrate undulatory motion will of necessity include several segments. The material selected to serve as the notochord (backbone) of the skeletal system for this phase is a polyurethane material (1/8" x 1" x 4"). This material is flexible, and has various grades of stiffness, and has good temperature and water absortion properties. Specification for this material are included in Appendix A. We selected a material which has a stiffness measure which approximates the bias force of the nitinol wire thus eliminating the need to provide an external bias force. Figure 5a is a photo of a single segment used for initial experimentation. The vertebrae are made of teflon and each has 4 holes spaced 1/8" apart (from center) which serve as optional attachment points for the wires. The photo also shows tuners (harpsichord) which were used to adjust the initial SMA wire tension.

Contraction and Relaxation Speed

A series of experiments was conducted with the above single segment configuration prior to conducting experiments with a multi-segment configuration. A sensor was used to measure motion of the segment (perpendicular to the notochord axis), and it's output voltage versus deflection and contraction force required is shown in Figure 6. Experiments were carried out to assess contraction and relaxation times (hence cycle rate) both in air and in water at about 20 degrees C.

Experiments in air single segment Plots of contraction time and relaxation time versus peak current input in air is shown for 150 micron wire (70 degrees C wire) in figures 7. Note the pronounced decrease in contraction time as the current amplitude is increased (ie pulse width is decreased). For a fixed ampere-seconds product input, the total time for contraction and relaxation appears to be very nearly a constant. This constant essentially determines the maximum cycle rate for the wire under the existing ambient conditions.

Smaller diameter wire cools faster than the larger diameter wire. This is due to the larger surface to mass ratio for the smaller wire. For the 150 micron wire in air with a small cooling fan, the maximum cycle rate is about 1.1 seconds whereas it is about 0.7 seconds for the 100 micron wire. For a single segment having antagonistic wires on each side this implies a cycle rate of 2.2 seconds (0.45hz) and 1.4 seconds (0.7 hz) respectively for these two size wires. This is demonstrated in Figures 8a and 8b. Notice in these plots that a delay is required between alternate side activation to allow the wire to cool and begin to relax. This side to side activation delay is important and must be included when designing multiple segment coordination strategies as will be seen later.

Experiments in water single segment The same single segment system (100 micron wire) was immersed in de-ionized water at room temperature to measure the effects of liquid cooling on the

FIGURE 5A. SINGLE SEGMENT

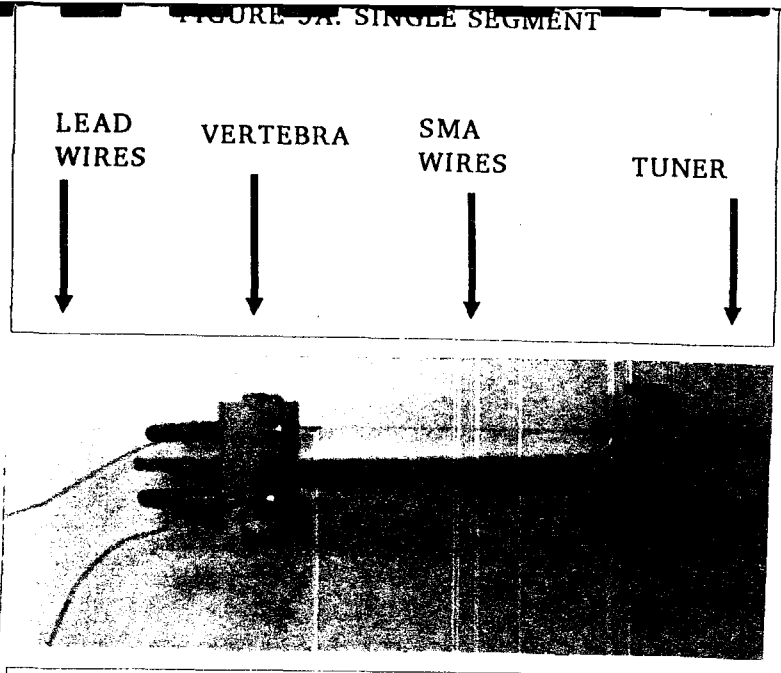



FIGURE 5B. 4 SEGMENT SKELETAL SYSTEM

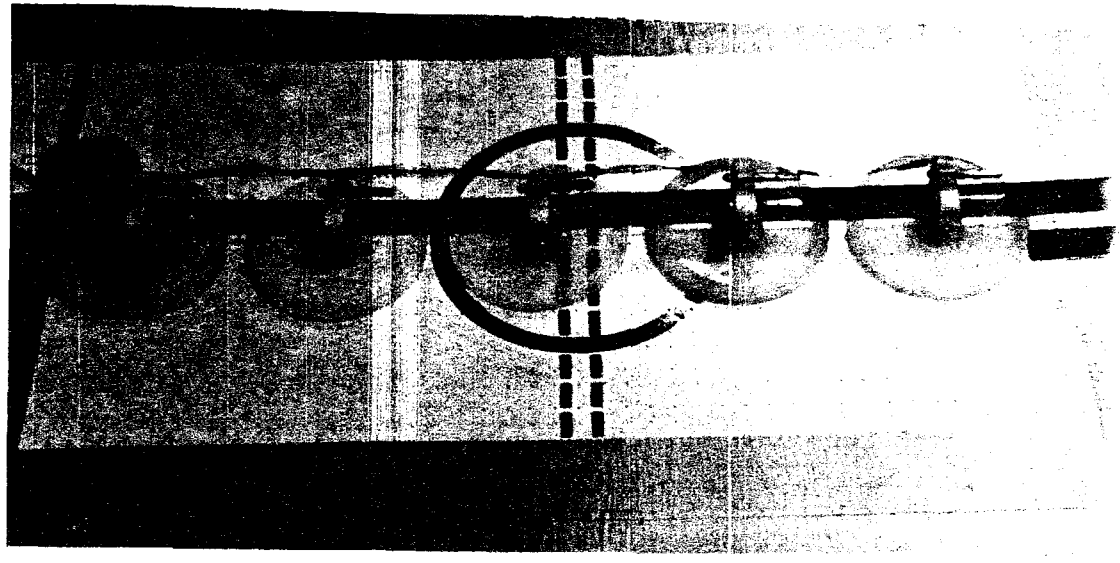
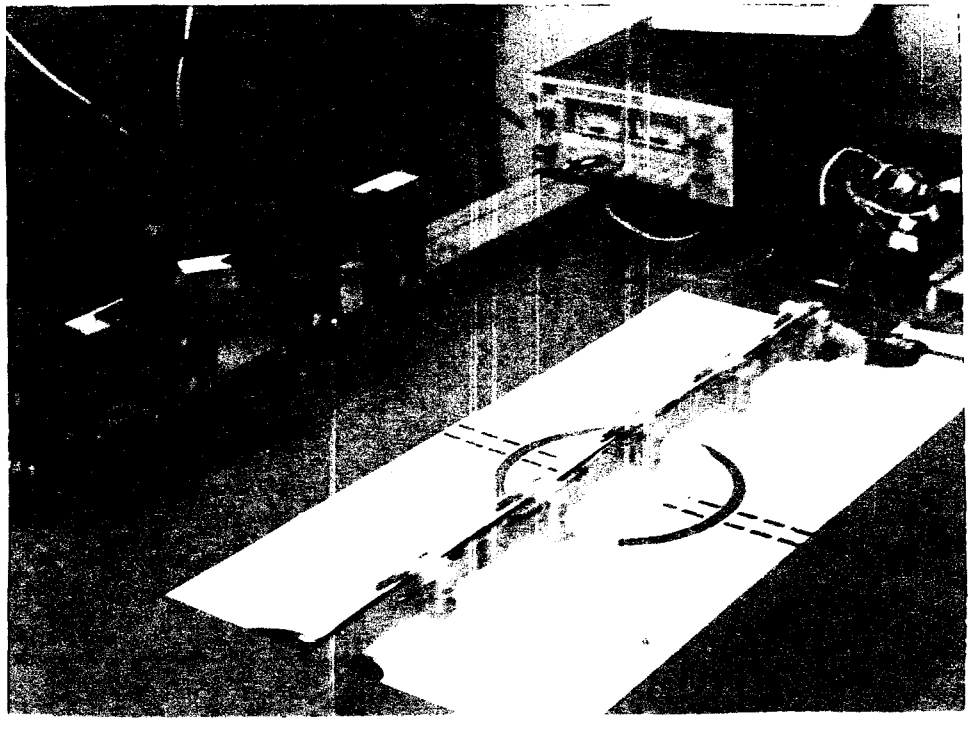


FIGURE 5C. 4 SEGMENT TEST CONFIGURATION



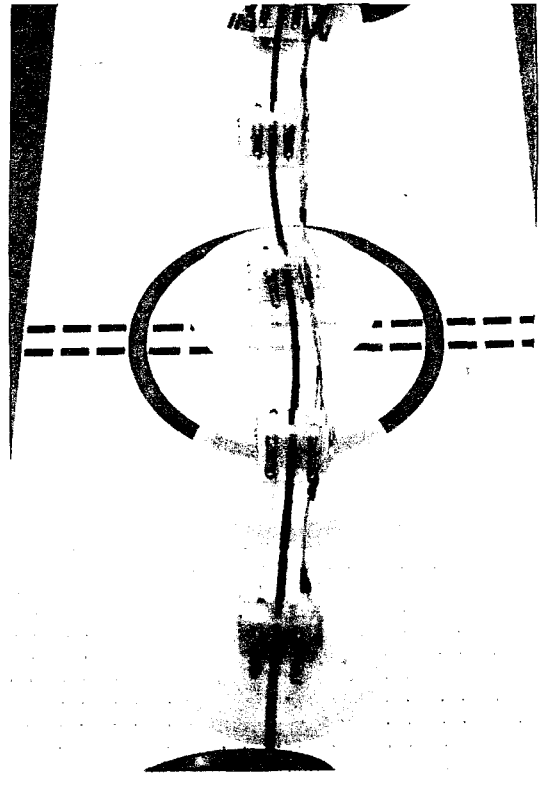


FIGURE 5D

LAMPREY - LIKE UNDULATION

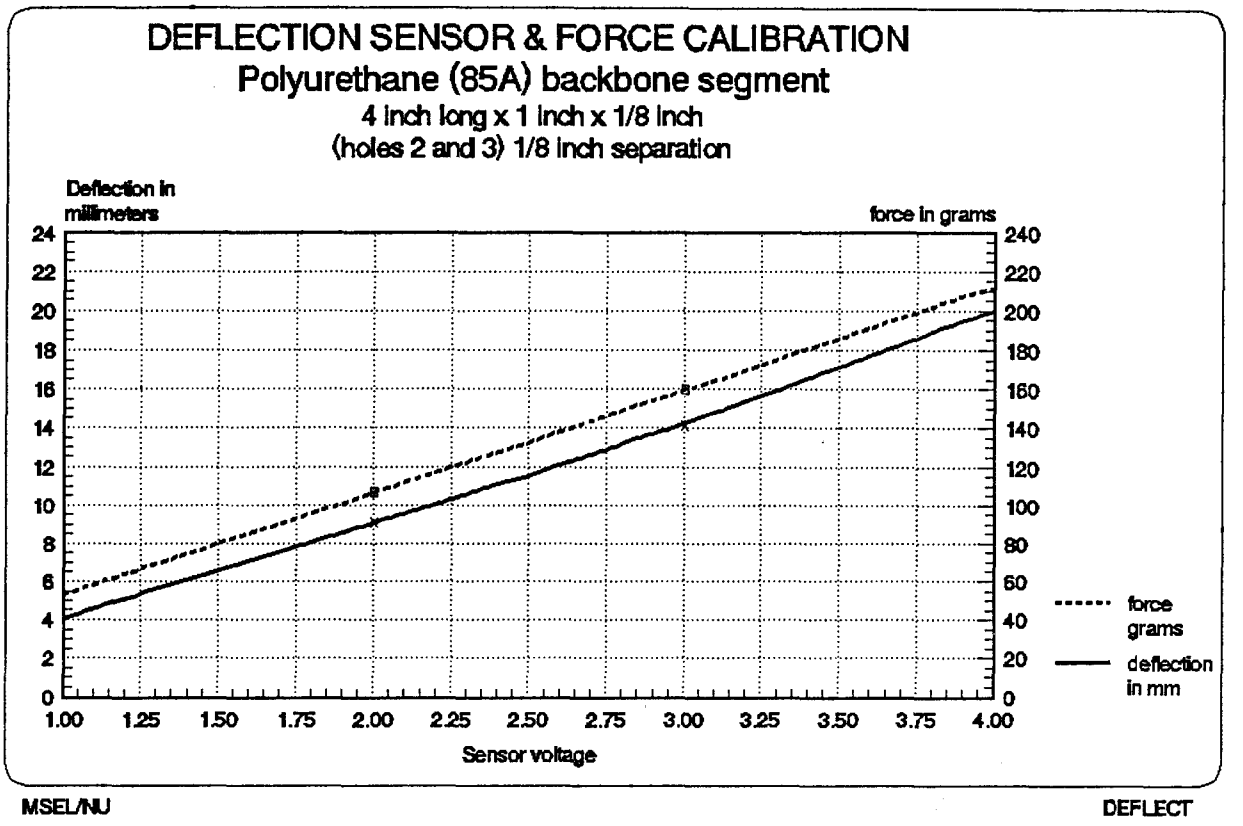

DEFLECTION SENSOR & FORCE CALIBRATION
Polyurethane (85A) backbone segment
4 inch long x 1 inch x 1/8 inch
(holes 2 and 3) 1/8 inch separation
Deflection in millimeters
force in grams
24
22
20
18
16
14
12
10
8
6
4
2
0
240
220
200
180
160
140
120
100
80
60
40
20
0
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
Sensor voltage
force grams
deflection in mm
MSEL/NU
DEFLECT

Figure 6

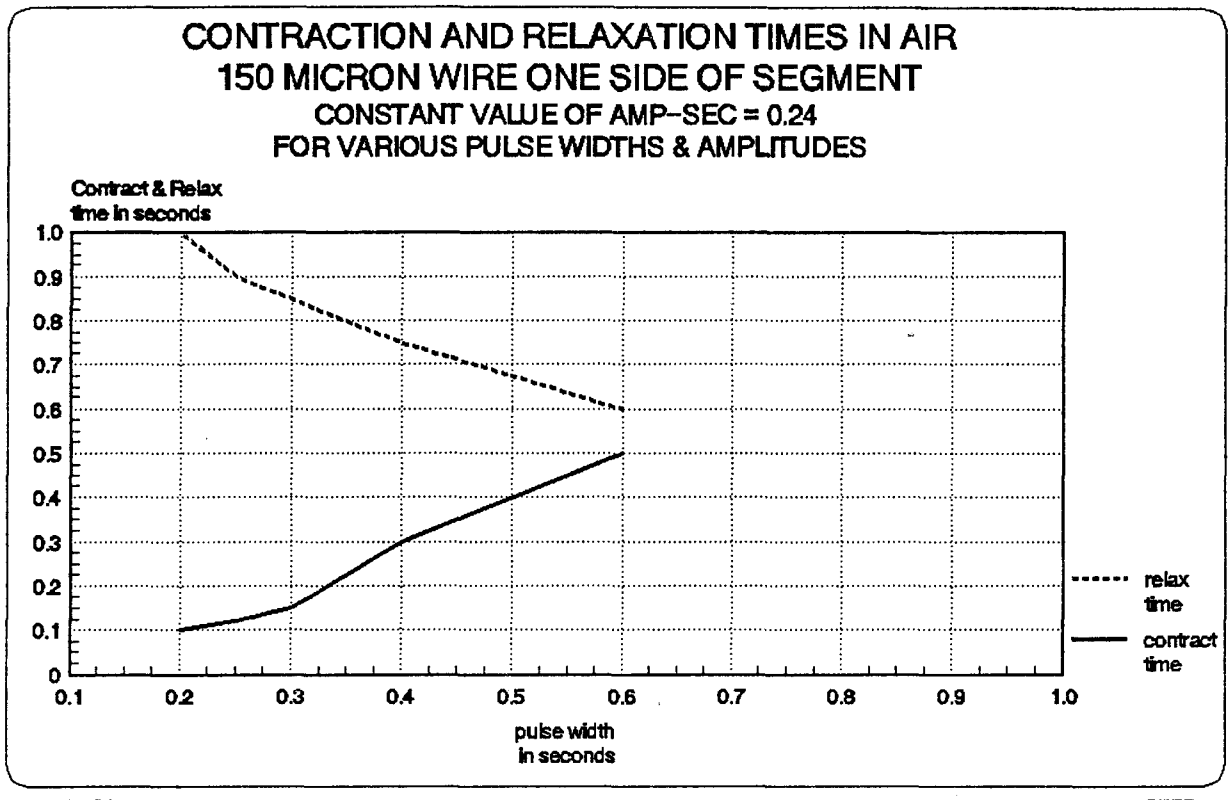

CONTRACTION AND RELAXATION TIMES IN AIR
150 MICRON WIRE ONE SIDE OF SEGMENT
CONSTANT VALUE OF AMP-SEC = 0.24
FOR VARIOUS PULSE WIDTHS & AMPLITUDES
Contract & Relax time in seconds
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
pulse width in seconds
relax time
contract time
MSEL/NU
SPEED

Figure 7

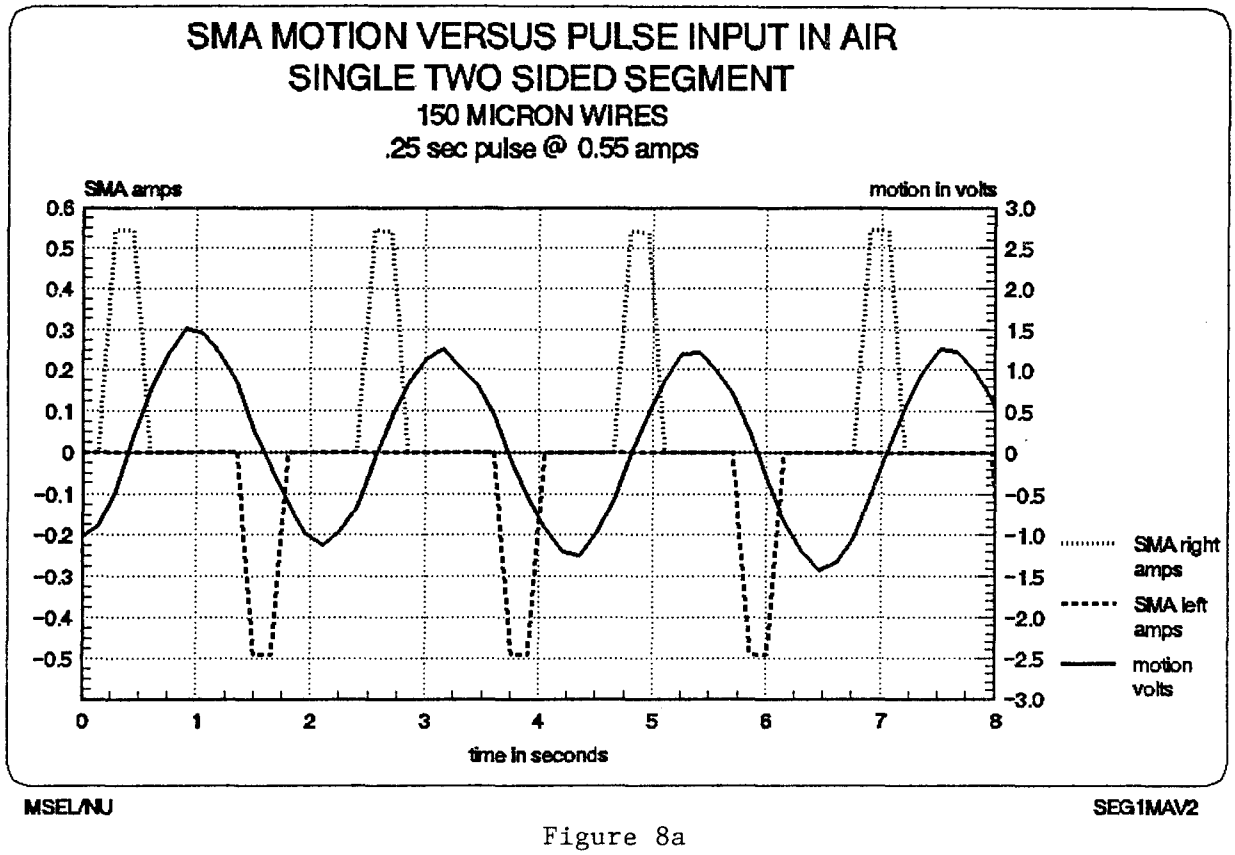



Figure 8a

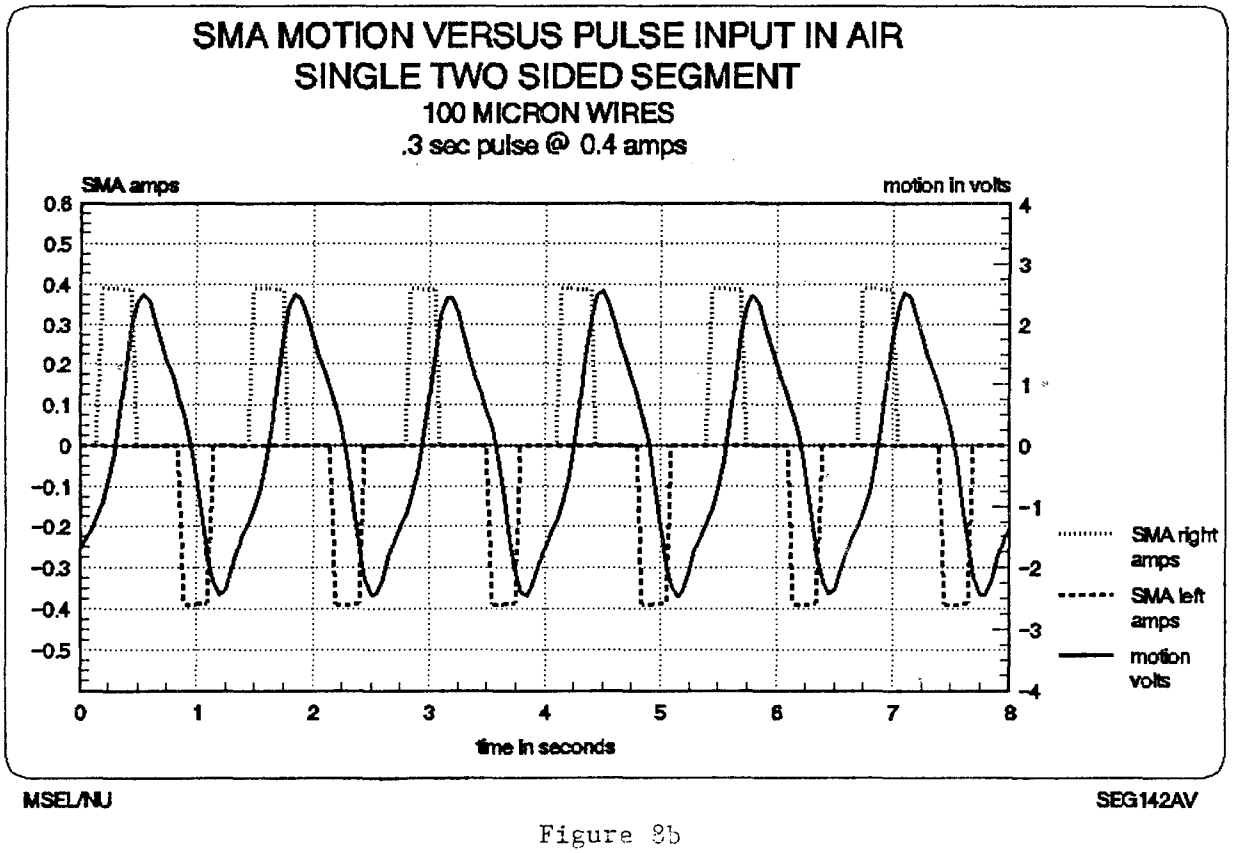



Figure 8b

relaxation time of the SMA wires and to measure the power required in this environment. The results show that the cycle rate for a single wire is about 0.13 seconds resulting in a cycle rate of 0.26 seconds for a two wire segment. Figure 9 is a plot of the drive current signals and the resulting oscillatory motion of a segment in water. The frequency of oscillation in water is about 4 hertz as compared to 0.7 hertz in air. For a single wire in water the average current requirement was 0.4 amps hence each wire is operating at a 0.4 amp-hr rate at 4 hertz operating frequency. For a 4 segment undulatory system in 20 degree C water, this would amount to a 3.2 amp-hr rate at 18 volts.

SMA current amplitude in water In Figure 10 we have plotted the SMA current amplitude at a fixed pulse width (pulse width = 63 msec) versus notochord deflection. This data was acquired during the in water experiments. The data shows that segment deflection or motion is proportional to the amplitude of the applied current. This is significant in terms of controlling the amplitude of oscillation of a multi-segment undulatory system as will be seen later.

## 4.3 Four Segment Undulatory System Experiments

### 4.3.1 Mechanical configuration

A simple skeletal system was designed and constructed for the purpose of conducting experiments aimed at demonstrating undulatory motion. It was determined that by making use of a continuously flexible backbone system that fewer SMA actuators would be required to show smooth undulatory behavior. As mentioned earlier the backbone material is polyurethane (Durometer 85A) manufactured by Harkness Industries (Appendix A). Photos of the skeletal system and test configuration are shown in Figures 5b and 5c. The total length of the backbone is 2 feet long, and it is 1 inch high, and 1/8 inch thick. It has 5 solid teflon vertebrae located 4 inches apart. They serve as attachment points for the SMA wires and for tuners which are used to adjust initial wire tension. The configuration uses single 3 inch SMA wires (100 micron diameter) on each side of each segment for a total of 8 wires.

### 4.3.2 Neural control system

Typical neural control signal timing which governs muscle actuation of Lampreys or Eels are depicted in Figure 11 for a 4 segment system. The upper (positive) traces depict left side activation while the lower (negative) traces depict right side activation. The center traces depict those closest to the head and the farthest from the center those closest to the tail. The delay is represented as the time between activation of successive segments on a given side and the body flexure wave activation frequency is determined by the cycle time of the first segment.

A circuit was designed and fabricated to generate the necessary signals and to drive the SMA wires. The circuit allows for

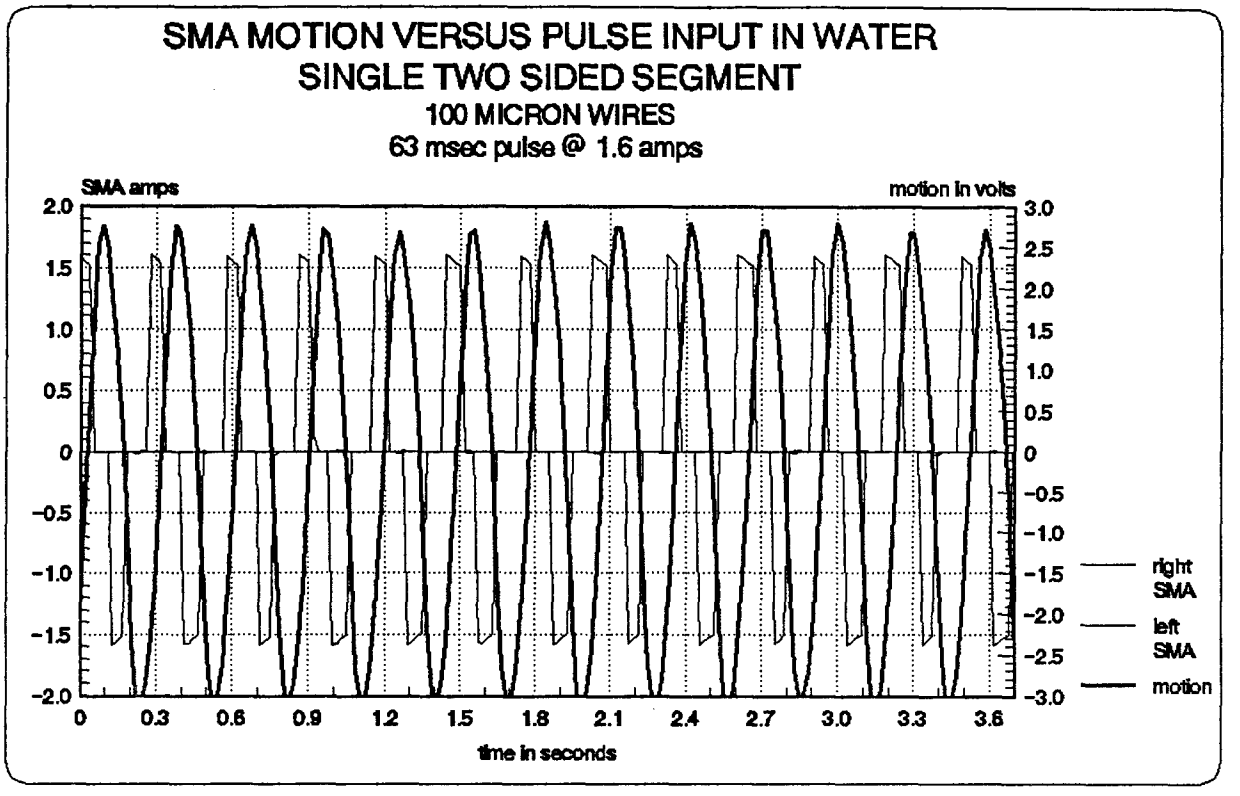



Figure 9

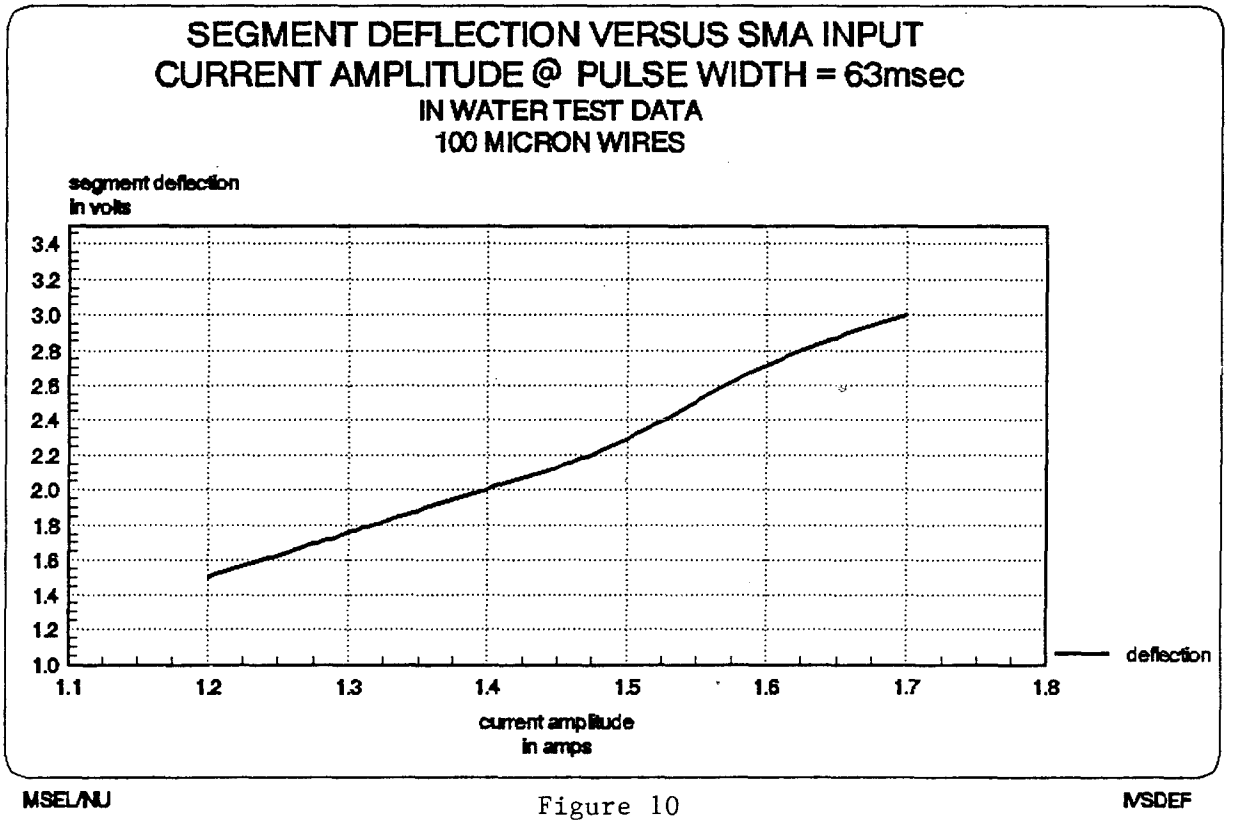



Figure 10

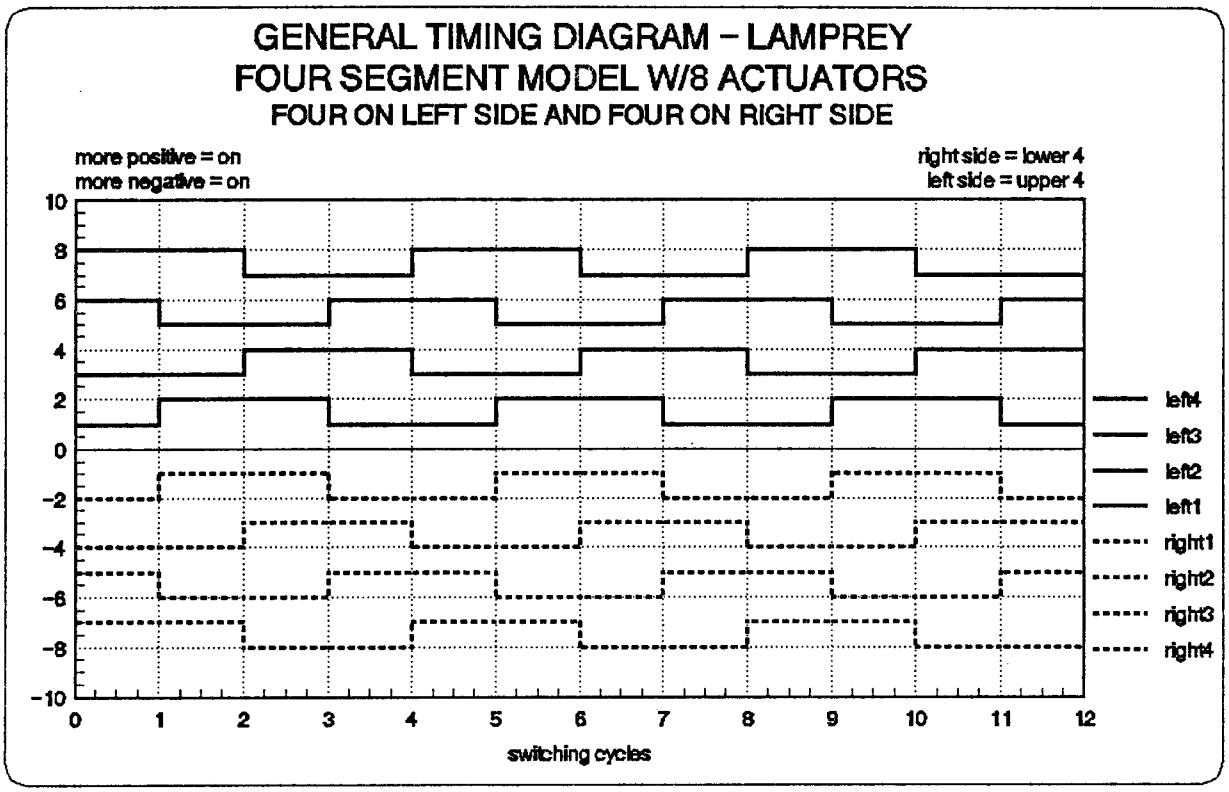



Figure 11

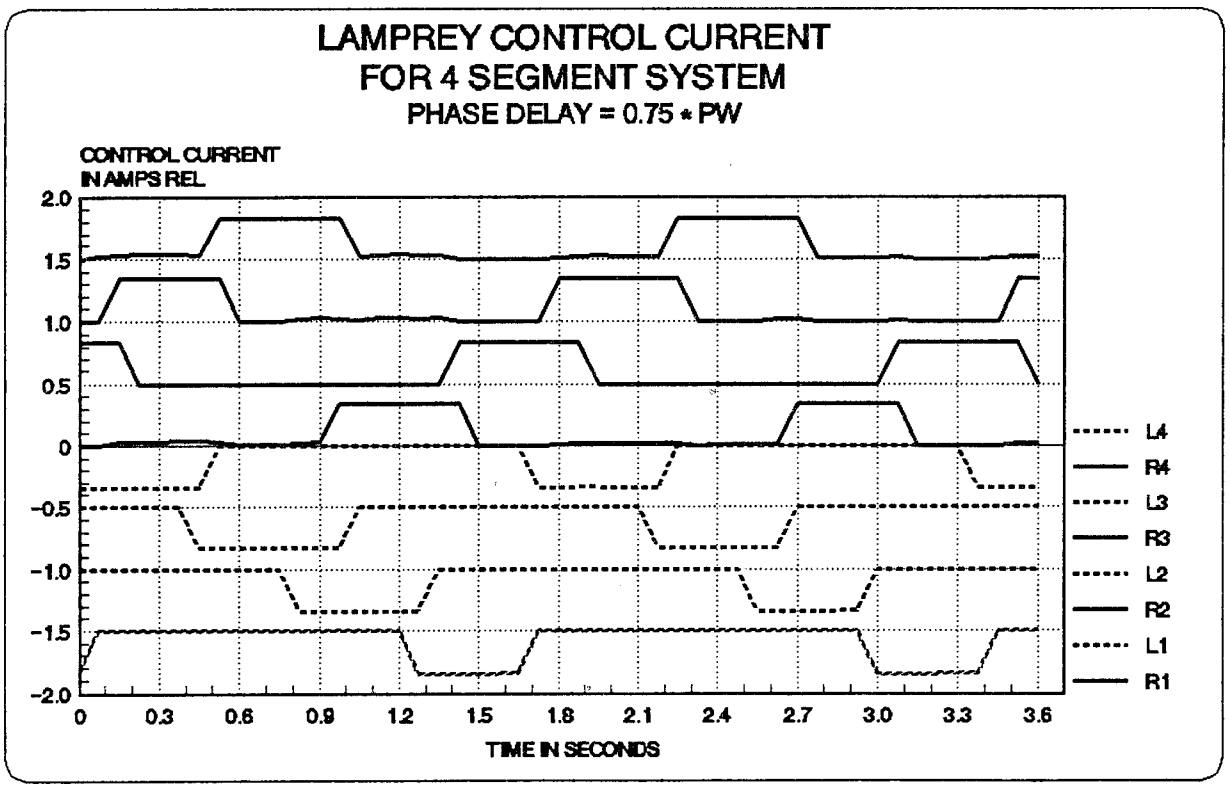



Figure 12

changing the each of the pulse widths (duration), pulse frequency (cycle time), intersegment phase delays, and signal amplitude. These signals will later be generated and controlled by a small microprocessor. Figure 12 depicts the actual control signals generated by the circuit. Notice that there is a built in delay between activation of antagonistic sides of an individual segment. This is required to allow for the SMA wire's finite relaxation time (cooling time) prior to activating the opposite side.

### 4.3.3 Experimental Setup and Data Acquisition System

The experimental system setup is shown in Figure 5c. The undulatory system was placed on an air table to minimize friction drag due to gravity. Four ultrasound sensors were used to track the motion of each of the four vertebrae during operation. The ultrasound sensor frequency was 215 kHz and the output is a continuous analog output voltage proportional to distance from the transducer head. These sensors were operated at 100 hertz sampling rate.

The components of the data acquisition system included a DT-2801A Data Translation board which was mounted in a laboratory PC. It provides for sixteen 12 bit A/D channels with a 27.5 kHz throughput and selectable gain. It also has two 12 bit D/A outputs and two 8 line digital I/O ports and a programmable clock. The system was programmed to sample the voltage across each of the 8 SMA actuators as well as the output from the four transducers. The data were then plotted and printed from a PC using a graphical plotting program.

An 8mm video camera and recorder were used to document and further analyze the motion resulting from a variety of neural control configurations. Additionally, a VHS video camera was used to document various experiments. A 6 minute narrated video was produced depicting the results of this phase of the project.

### 4.3.4 Experimental results - four segment undulator

We investigated four types of coordination which correspond to the four types of synergies described earlier for steady swimming of different fish.

The first type of coordination is similar to that of a Lamprey or Eel. The control signals and the resulting vertebral motion is depicted in Figure 13a, and 13b respectively. The pulses in each segment are the same width, and the activation delay is equal to the deactivation delay. The phase delay in this configuration is 3/4 (0.75) of the pulse width (PW) (see calculations in appendix C). In this configuration, the first segment of the left side is activated at about the same time as the third segment on the right side. The nominal amplitude of the current pulses in each wire is about 0.35 amps and the cycle time is 1.7 seconds. The oscillatory motion of the vertebrae is quite smooth and the progression of the motion (wave) from the first segment (MOVE1) to the fourth (MOVE4) is obvious. One can also see the

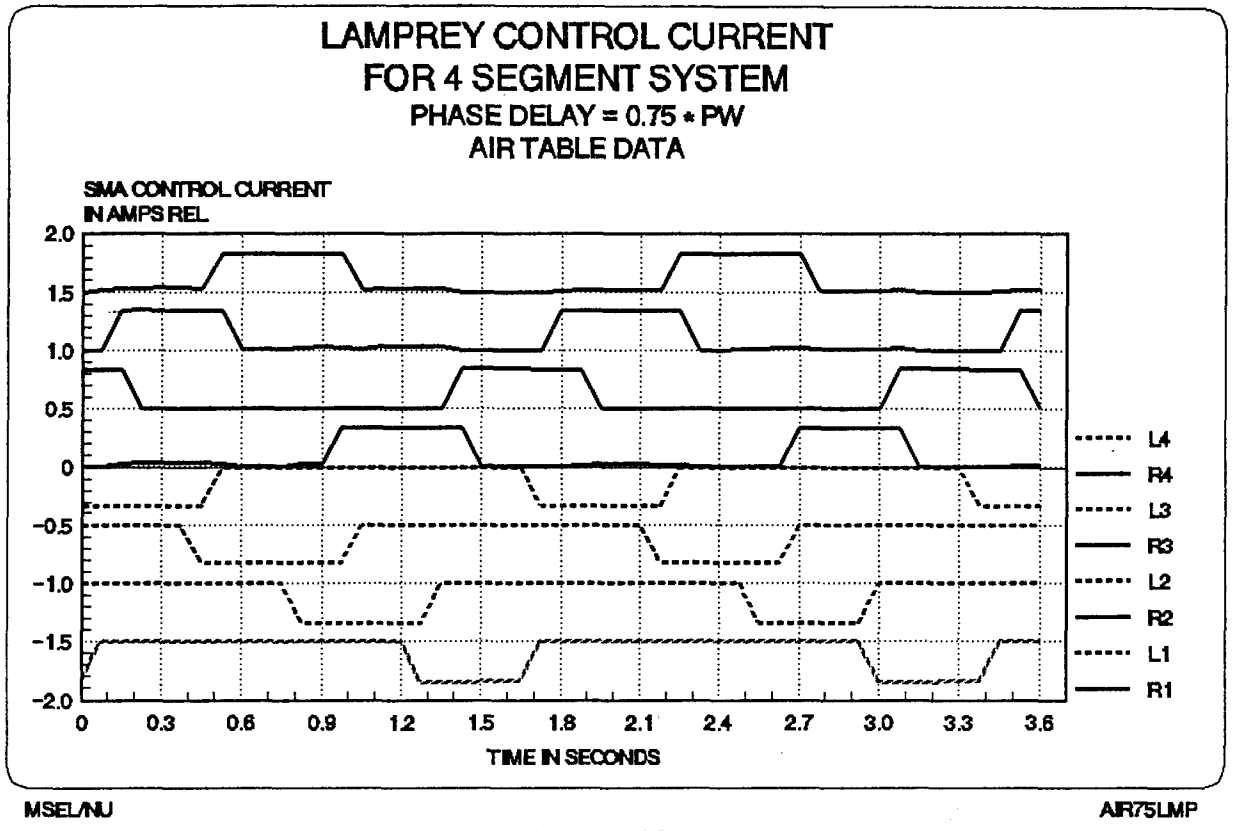



Figure 13a

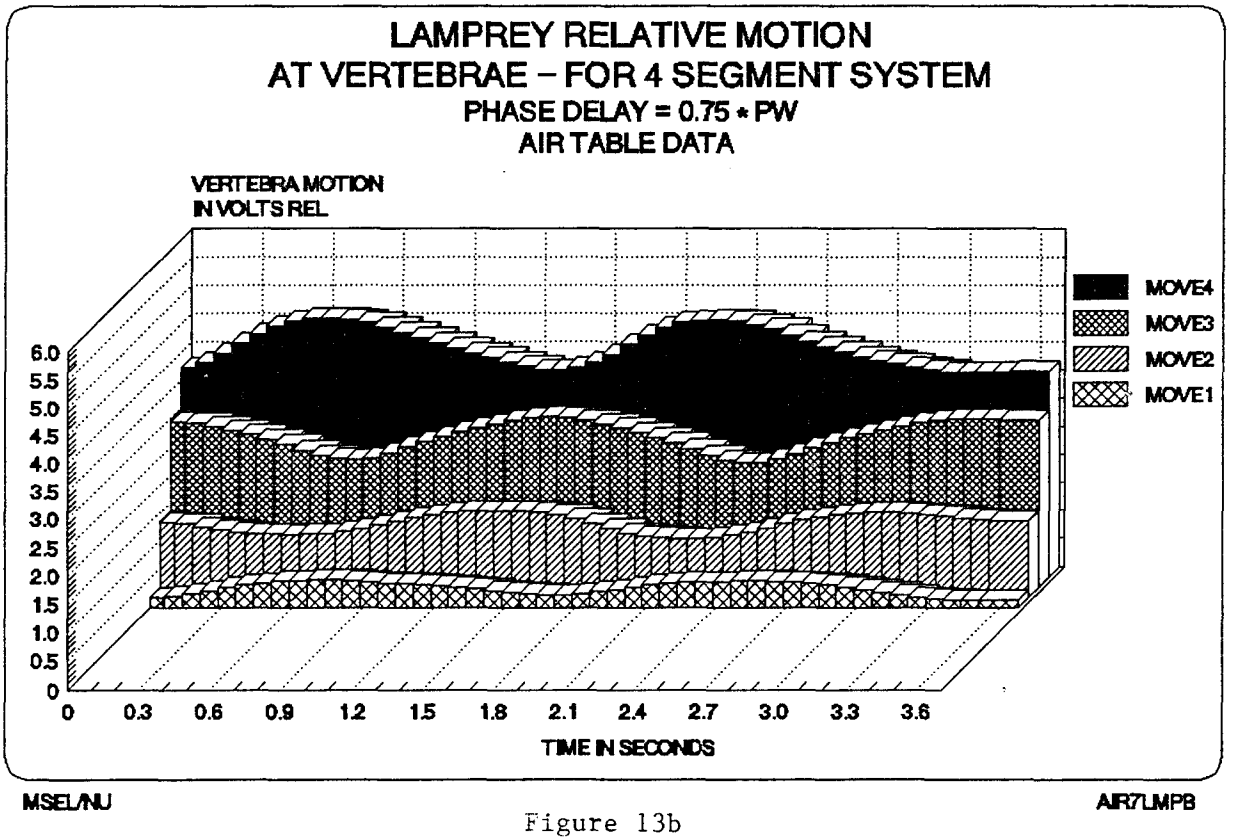



Figure 13b

resultant motion in the photo of Figure 5d.

The second coordination type (Carp) involved reducing the phase delay between segments. All other parameters (pulse width, side to side delay, and current amplitude) remained essentially the same as in the first type. Figure 14a and 14b show the control signals and the resultant vertebral motion of the system. This type of coordination leads to having a larger percentage of body length activation with time on a given side and results in a larger amplitude motion at the tail (fourth segment) of the system.

The third type (Trout) of coordination is a much like a combination of types one and four. The phase delay is 3/4 of the pulse width of the first segment but the activation pulse widths decrease along the body. There is, however, side to side overlap of activation (unlike the shark). The resultant motion is oscillatory (Figures 15a, 15b).

The fourth coordination configuration is similar to that of a shark. Figures 16a and 16b depict the control signals and resultant vertebral motion response. The phase delay in this configuration is one fourth (0.25*PW) of the first segment's pulse width. The basic cycle time (1.7 seconds) is the same as all cases described above. Notice that each successive pulse width is decreased along one side of the body and that there is no side to side overlap of activation. Also notice that the activation of all segments on a given side terminate simultaneously. The result is that an undulatory wave is not discernible. The motion as seen on the video is more like a side to side whipping action.

### 4.3.5 Discussion

The above experiments were carried out using a skeletal system. The system body mass and its relative distribution, to simulate specific types of fish, were not incorporated in this phase hence the resultant motion does not exactly replicate that of specific coordination types. The Lamprey or Eel response, however, is a closer approximation since their mass is more equally distributed than the other types (Figures 1a and 1b).

The experiments carried out on the 4 segment system above were all conducted in air. Based on our single segment experiments in water as described earlier, it appears that the cycle time of the 4 segment system could be reduced from 1.7 seconds to about 0.25 seconds (4 hertz). This is close to an order of magnitude improvement in flexion wave frequency due to the faster cooling time in room temperature water. This oscillatory response frequency coincides with nominal frequencies of fish this size.

The tradeoffs for developing undulatory systems similar to that described here are: (1) Improvement in frequency of undulation for a given wire size can be achieved by immersion in a liquid bath, however at a cost of increased SMA power require-

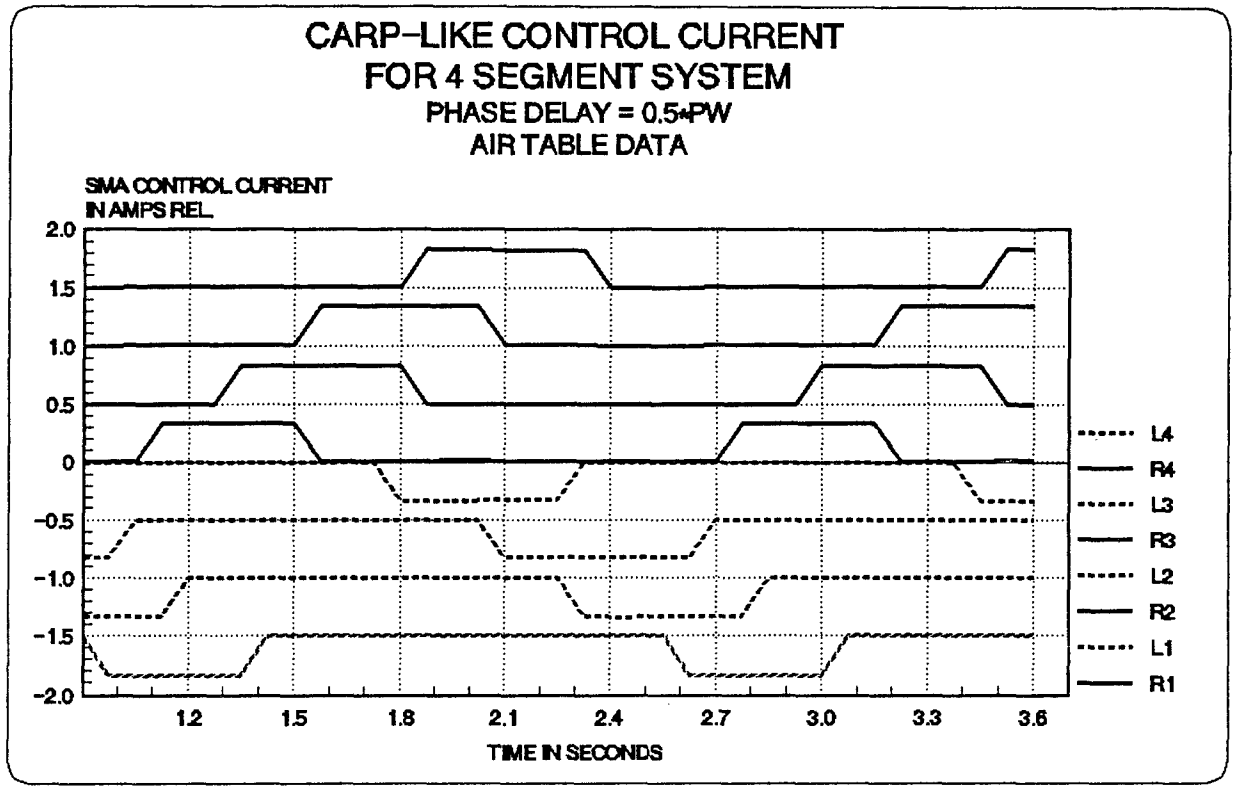



Figure 14a

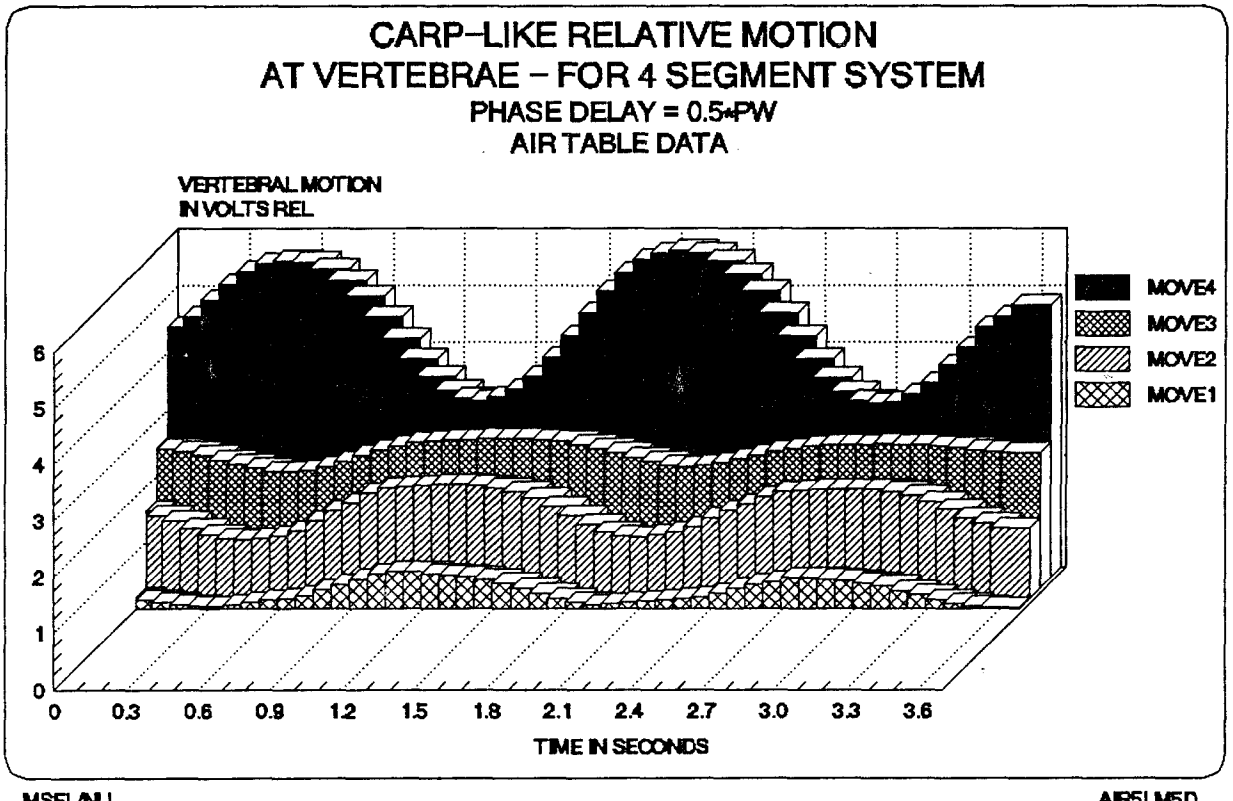



Figure 14b

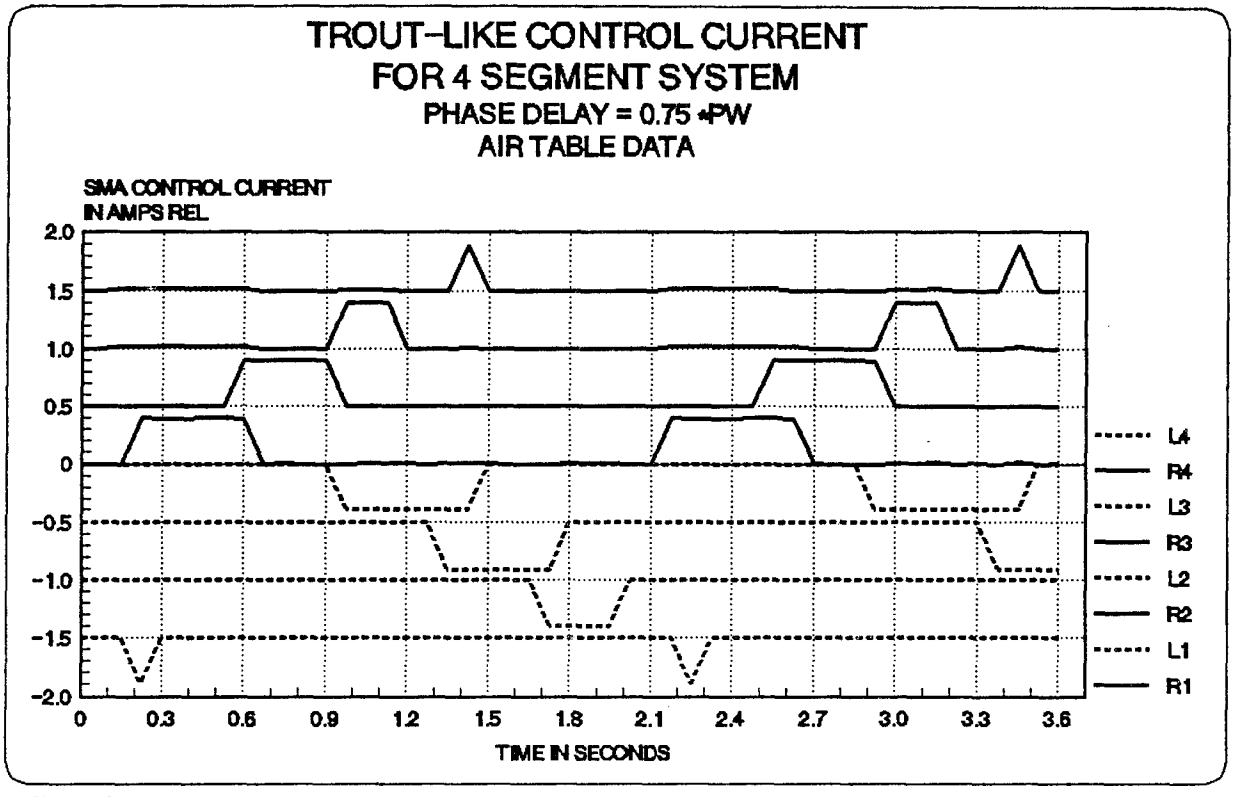



Figure 15a

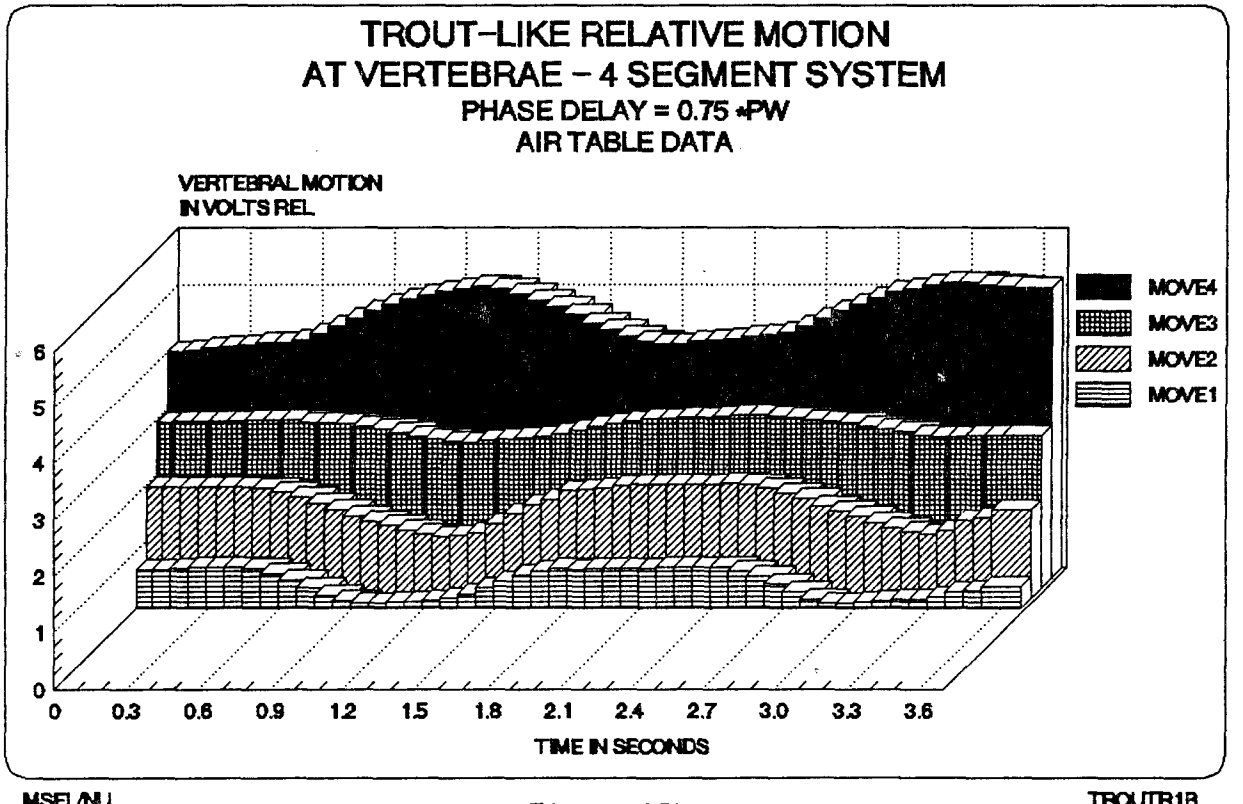



Figure 15b

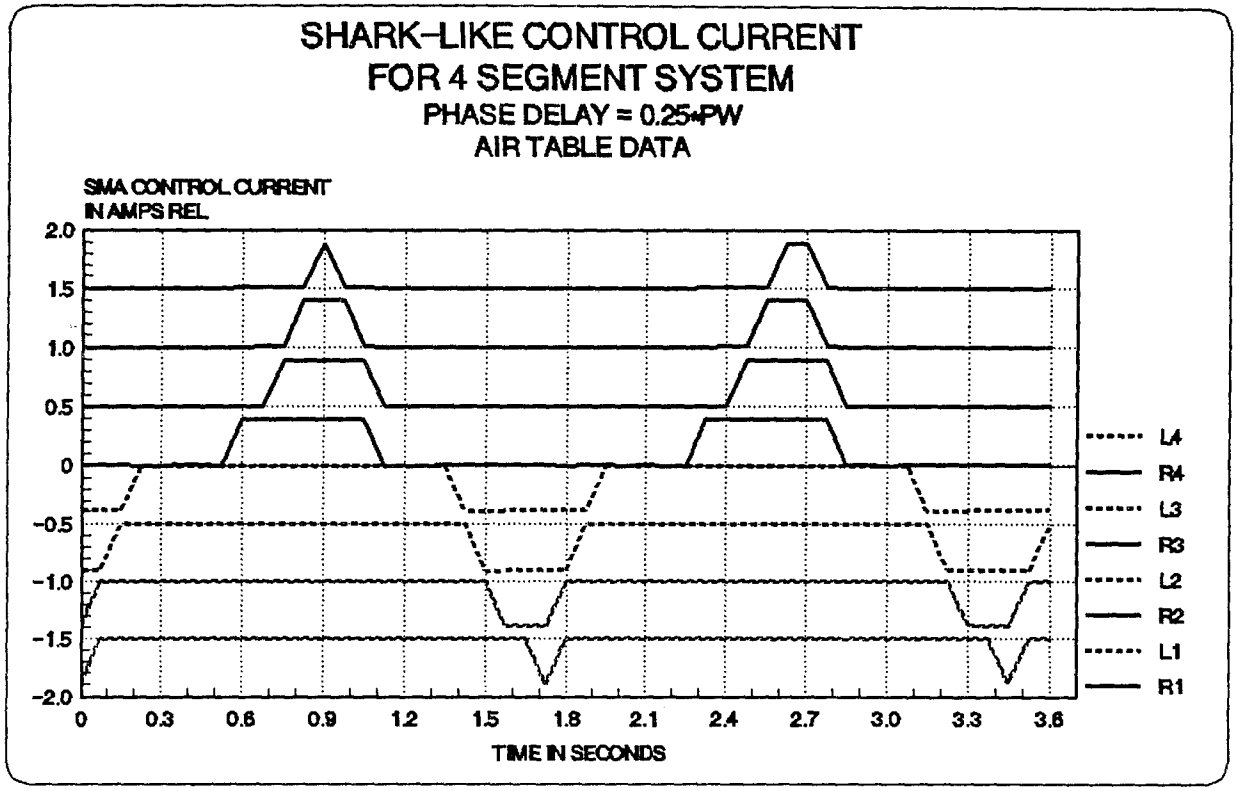



Figure 16a

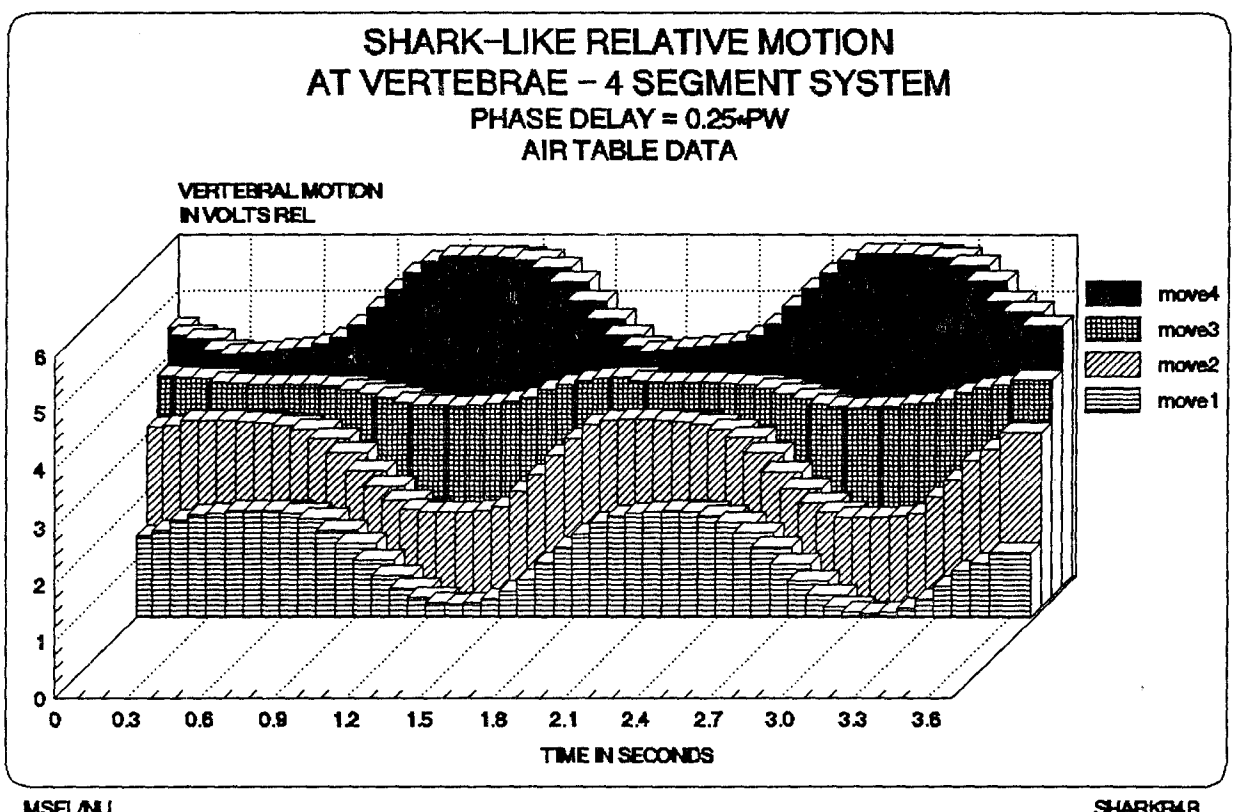



Figure 16b

ments. (2) The minimum size wire which can provide the required force will have the fastest response time. (3) If the contraction is maintained to about 3 percent, the wires can withstand hundreds of thousands of cycles of operation.

We ran a brief life cycle test of an SMA wire attached to a single segment system. The wire ran over 110, 000 cycles and was still operable. Further life cycle testing will be conducted during the next phase.

We have been experimenting with using type K (Nickel-Chromium vs. Nickel-Aluminum) thermocouples (at the suggestion of Ian Hunter and Serge Lafontaine) to measure SMA wire temperature under transient conditions. This could prove to be an excellent feedback mechanism for undulation control. We can measure temperature change in the wire with applied current, however, the thermocouple as tested was influenced by ambient conditions. We will be further investigating means of insulating the thermocouple from the environment as well as acquiring data on temperature versus time profiles relative to current input for various ambient environments.

## 5. SUMMARY OF RESULTS AND CONCLUSIONS

A skeletal system was developed to investigate fish like swimming characteristics. It provided for segmentation of a body and for propagation of waves of flexure along the body. The system consisted of 4 segments and a total length of 20 inches.

The system was used to demonstrate frequencies of 0.7 hertz in air and a potential for 4 hertz in 20 degree C water. The latter is similar to frequencies encountered in swimming fish of comparable size.

A polyurethane material was used to imitate a fish notochord and served to provide a restoring (bias) force for the muscle wires.

Shape memory alloy wires of 100 micron diameter were used as muscles. They produce about 3% contraction when pulses of current were applied. The contraction speed and developed force is related to the risetime, amplitude, and duration (which causes heating of the SMA wires) of the current pulse input. The restoration (relaxation) to original length is assisted by the elastic force of the polyurethane notochord.

Each segment consisted of left and right shape memory alloy "muscles" attached to solid teflon vertebrae. Each wire was initially tuned by hand using harpsichord tuners. The left and right wires were made to contract alternately in counterphase.

Coordination of segments was controlled by an electronic module. Four types of synergies were evaluated. They differ in terms of phase delay between segment activation, deactivation, and activation pulse width. The coordination types were selected

to agree with those developed from experiments with intact fishes.

This phase of the project demonstrated very clearly that the basic mechanisms for generating undulatory motion similar to that of fish in small robotic systems are realizable.

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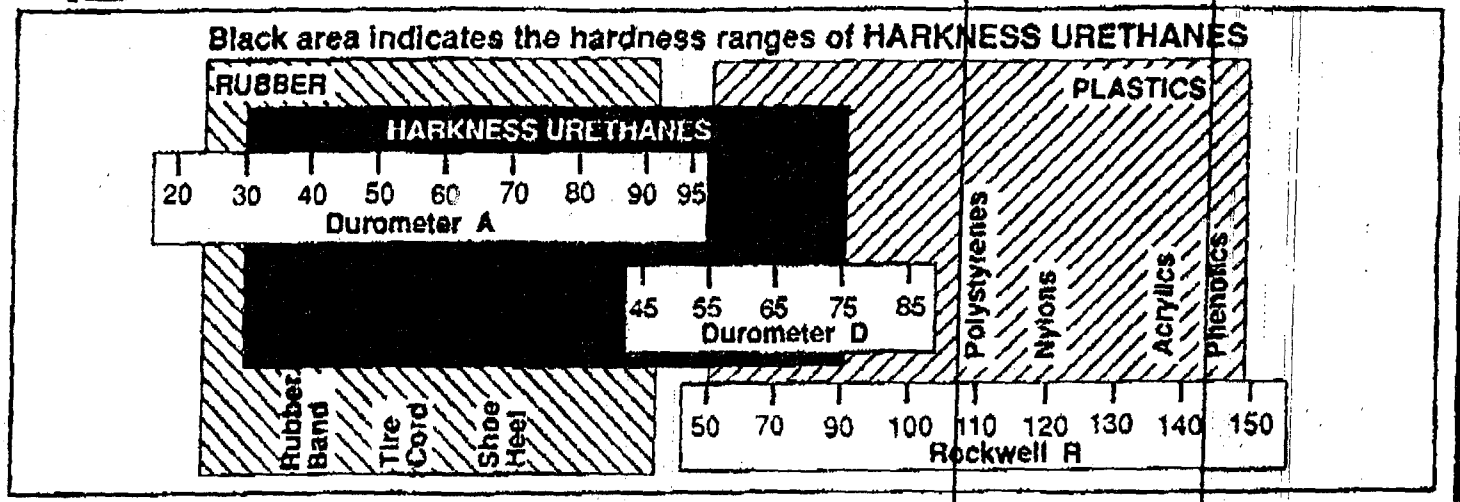
# Appendix A

## POLYURETHANE DATA SHEETS

# HARKNESS Industries. Inc.




# URETHANE PRODUCT GUIDE

| MECHANICAL PROPERTY | ASTM | MP300 | MP600 | MP750 | MP850 | MP900 | MP950 | MP160 | MP175 |
|---|---|---|---|---|---|---|---|---|---|
| **Tensile Properties** | Test | | | | | | | | |
| Break, psi | D-412 | 380 | 4500 | 5500 | 6000 | 4500 | 5500 | 6500 | 7500 |
| 100% modulus, psi | D-412 | 80 | 250 | 350 | 600 | 1100 | 1800 | 3000 | 5500 |
| 300% modulus, psi | D-412 | 170 | 600 | 1000 | 1500 | 2100 | 4000 | 6500 | – |
| Elongation, % | D-412 | 515 | 500 | 500 | 500 | 450 | 320 | 300 | 225 |
| Break Set, % | D-412 | – | 5 | 10 | 10 | 10 | 10 | 15 | – |
| Modulus of Elasticity, psi | D-638 | – | 500 | 1500 | 2500 | 5000 | 9000 | 12500 | – |
| **Compression Properties** (Shape factor 0.56) | | | | | | | | | |
| Deflection, psi @ 5% | D-575 | 15 | 30 | 70 | 130 | 310 | 450 | – | – |
| Deflection, psi @ 10% | D-575 | 25 | 70 | 140 | 390 | 625 | 890 | – | – |
| Deflection, psi @ 15% | D-575 | 34 | 110 | 220 | 560 | 875 | 1170 | – | – |
| Deflection, psi @ 20% | D-575 | 38 | 160 | 280 | 690 | 1125 | 1400 | – | – |
| Deflection, psi @ 25% | D-575 | 44 | 220 | 330 | 800 | 1350 | 1600 | – | – |
| **Compression Set, %** | | | | | | | | | |
| Method A @ 70° C | D-395 | – | 10 | 8 | 5 | – | 1 | 10 | 15 |
| Method B @ 70° C | D-395 | 9 | 10 | 15 | 25 | 30 | 40 | 50 | – |
| **Durometer**, Shore ± 5 | D-2240 | 30A | 60A | 75A | 85A | 90A | 95A | 60D | 75D |
| **Tear Properties**, pli, Die C | D-624 | 90 | 200 | 250 | 400 | 400 | 450 | 700 | 850 |
| **Abrasion Resistance**, Tabor | | | | | | | | | |
| H18 @ 1000gm. load, mg. loss per 1000 cycles | C-501 | – | 30 | 40 | 40 | 30 | 40 | 80 | 450 |
| **Specific Gravity** | D-792 | 1.20 | 1.26 | 1.26 | 1.26 | 1.10 | 1.15 | 1.18 | 1.18 |
| **Base** | | Ester | Ester | Ester | Ester | Ether | Ether | Ether | Ether |

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# Comparison of Harkness polyurethane with natural and synthetic rubbers

| PROPERTIES | | NATURAL RUBBER | SBR OR BUNA S butadiene styrene | BUTYL isobutylene isoprene | NITRILE (BUNA N) butadiene acrylonitrile | SILICONE polysiloxane polymer | NEOPRENE chloroprene | VITON copolymer of vinylidene fluoride and hexafluoropropylene | HYPALON chlorosulfonated polyethylene | Harkness polyurethane |
|---|---|---|---|---|---|---|---|---|---|---|
| TENSILE STRENGTH (psi) | Pure gum | Over 3000 | Below 3000 | Over 1500 | Below 1000 | Below 1500 | Over 3000 | Over 2000 | Over 2500 | 5000-8500 |
| | Black loaded stocks | Over 3000 | Over 2000 | Over 2000 | Over 2000 | | Over 3000 | Over 2000 | Over 3000 | |
| HARDNESS RANGE (durometer A) | | 30-90 | 40-90 | 40-75 | 40-95 | 40-85 | 40-95 | 60-95 | 40-95 | 50-99+ (up to 75 durometer D) |
| SPECIFIC GRAVITY (Base Material) | | 0.93 | 0.94 | 0.92 | 1.00 | | 1.23 | 1.65 | 1.12-1.28 | 1.10 to 1.24 |
| VULCANIZING PROPERTIES | | Excellent | Excellent | Good | Excellent | | Excellent | Good | Excellent | Excellent |
| ADHESION TO METALS | | Excellent | Excellent | Good | Excellent | | Excellent | Good to excellent | Excellent | Excellent |
| ADHESION TO FABRICS | | Excellent | Good | Good | Good | | Excellent | Good to excellent | Good | Excellent |
| TEAR RESISTANCE | | Good | Fair | Good | Fair | Poor | Good | Fair | Fair | Outstanding |
| ABRASION RESISTANCE | | Excellent | Good to excellent | Good | Good | Poor | Excellent | Good | Excellent | Outstanding |
| COMPRESSION SET | | Good | Good | Fair | Good | Fair | Fair to good | Very good | Fair | Good |
| REBOUND | Cold | Excellent | Good | Bad | Good | Excellent | Very good | Good | Good | Fair at low temp. |
| | Hot | Excellent | Good | Very good | Good | Excellent | Very good | Excellent | Good | Good at room temp. |
| DIELECTRIC STRENGTH | | Excellent | Excellent | Excellent | Poor | Good | Good | Good | Excellent | Excellent |
| ELECTRICAL INSULATION | | Good to excellent | Good to excellent | Good to excellent | Poor | Excellent | Fair to good | Fair to good | Good | Good |
| PERMEABILITY TO GASES | | Fair | Fair | Very low | Fair | Fair | Low | Very low | Low to very low | Fair-Good |
| ACID RESISTANCE | Dilute | Fair to good | Fair to good | Excellent | Good | Excellent | Excellent | Excellent | Excellent | Fair-Good |
| | Concentrated | Fair to good | Fair to good | Excellent | Good | Fair | Good | Excellent | Very good | Poor |
| SOLVENT RESISTANCE | Aliphatic hydrocarbons | Poor | Poor | Poor | Excellent | Poor | Good | Excellent | Good | Excellent |
| | Aromatic hydrocarbons | Poor | Poor | Poor | Good | Poor | Fair | Excellent | Fair | Fair to good |
| | Oxygenated (ketones, etc.) | Good | Good | Good | Poor | Fair | Poor | Poor | Poor | Poor |
| | Lacquer solvents | Poor | Poor | Poor | Fair | Poor | Poor | Poor | Poor | Poor |
| | Swelling in lubricating oil | Poor | Poor | Poor | Very good | Fair | Good | Excellent | Good to excellent | Excellent |
| | Oil and gasoline | Poor | Poor | Poor | Excellent | Fair | Good | Excellent | Good | Excellent |
| | Animal and vegetable oils | Poor to good | Poor to good | Excellent | Excellent | Fair | Good | Excellent | Good | Excellent |
| | Water absorption | Very good | Good to excellent | Very good | Fair to good | Good | Good | Very good | Very good | Good at room temp. Fair at 175°F |
| RESISTANCE TO | Oxidation | Good | Good | Excellent | Good | Excellent | Excellent | Outstanding | Excellent | Outstanding |
| | Ozone | Fair | Fair | Excellent | Fair | Excellent | Excellent | Outstanding | Outstanding | Outstanding |
| | Sunlight aging | Poor | Poor | Very good | Poor | Excellent | Very good | Very good | Outstanding | Excellent |
| | Heat aging | Good | Very good | Excellent | Excellent | Outstanding | Excellent | Outstanding | Excellent | Good |
| | Flame | Poor | Poor | Poor | Poor | Fair | Good | Good | Good | Good |
| | Heat | Good | Excellent | Excellent | Excellent | Excellent | Excellent | Excellent | Excellent | Good |
| | Cold | Excellent | Excellent | Good | Good | Excellent | Good | Good | Good | Excellent |